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A TIME AND SPACE STUDY OF POLLUTANTS

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A Time & Space Study of Pollutants

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Introduction

The original intention of this research was to study the time and space variations of sulfur dioxide and carbon monoxide over Houston, TX, Texas, with vertical changes being studied by sampling the free atmosphere from a helicopter. However, the results of ground level measurements taken during the early period of our grant, and the report prepared by the Southwest Research Institute, showed that, even in the industrial complex, concentrations of sulfur dioxide were generally less than 0.5 pphm. Such values are near the threshold response of many instruments and these facts caused the focus of our investigations to be turned to the measurement of carbon monoxide. All scientific investigations need to have a sound experimental design. One fundamental aspect of this is a logical schedule for the studies.

After reviewing available data, reports and surveys, it was ~~we~~ decided that the following program presented ~~the best steps necessary~~ for an understanding of the overall meteorological problems related to a time and space study of air pollution in Houston.

(1) Obtaining, or knowing how to obtain, relevant meteorological data for climatological studies or during specific incidences of air pollution.

(2) Compilation of a source inventory for the area.

(3) Derivation of a numerical model for use in a chosen area.

(4) Study of the sampling techniques in use and available in the region.

(5) Measurements of the selected pollutants or their components.

(6) Urban climatology.

This is the order in which the different facets of this report are presented.

Abstract

(1) Climatological Studies

Climatological data are readily available for many ground-based stations in and around the Houston area. Unfortunately, many of these stations, even the airports, do not show the continuity of record that is desirable for an overall study of this nature. Information concerning temperature and rainfall are considered adequate but information on wind speed and direction is noticeably inadequate. The downtown station has the anemometer exposed on the roof, which gives rise to unusual patterns of speed and direction, while the new Intercontinental Airport is some 25 miles north of the city and its airflow need not necessarily be representative of that experienced in the actual downtown or industrial area. However, the greatest drawback to the climatological studies resulted from the lack of upper air information. It is absolutely necessary from the point of view of air pollution meteorology, to have information concerning temperature and wind speed data in the first few thousand feet of the atmosphere. These are fundamentals in any mathematical modeling. However, Houston has not had an upper air station for more than a decade and this lack of data necessitated an intermediate investigation.

This specific study was the subject of an M.S. thesis by Lt. Colonel James T. Zumwalt. In this investigation we have developed a technique for estimating the lower winds (winds up to about 2000 meters) over Houston, Texas, from the currently existing upper air

station at Lake Charles, Louisiana. This thesis is in the nature of a fundamental one because of its specific study of a seldom used statistical technique, namely spatial vector regression. From this it is shown that a simple technique is preferable, in this instance, to the more involved one derived a little later by a statistician. The outcome of this is that it is now possible, in the region from about 500 to 2000 meters, to estimate the winds aloft over Houston with sufficient accuracy for most air pollution meteorological studies. Owing to the pronounced and significant variation in the lower layers recourse must be had to the use of actually measured surface data.

Since the completion of this work it has been learned that, during late 1971, one of the Environmental Meteorological Support Units (National Oceanographic and Atmospheric Administration) will be located in Houston. This unit will take upper air (to 1000 ft) information and wind speed and direction on a regular basis, supplemented during times of severe air pollution potential.

ABSTRACT

(2) AREAL AND TEMPORAL DISTRIBUTION OF POLLUTANT EMISSIONS FROM VEHICLES IN HOUSTON

The areal and temporal variation of pollutant emissions into an urban atmosphere is a necessary boundary condition for the mathematical modeling of atmospheric diffusion. In this paper calculations are presented that show the pattern of emission of vehicular pollutants from a 760 mi^2 area containing the city of Houston and adjacent urbanized areas. The magnitudes of the emissions were determined assuming no control devices. Vehicle-miles of travel in each of 760 mile-square grid zones were used as proxies for pollutant emissions with emission factors being employed to convert vehicle miles into pollutant emissions. A technique was developed for computing vehicle-mileage on local streets which are often neglected in emission inventories. It is estimated that vehicles emit more than 2.4×10^6 lbs of major pollutants into the urban atmosphere over Houston.

Abstract

(3) Derivation Of A Numerical Model For Predicting Gaseous Diffusion In The Atmosphere

A numerical model is proposed for predicting the dispersion of SO_2 over Nashville, Tennessee, during the winter. The model includes the effects of three-dimensional advection, of diffusion, and of variations in the topography. Also included in the numerical solution are the effects of chemical decay, of source strength, and of a correction term for the truncation error. A variable, vertical exchange coefficient is incorporated in the diffusive portion of the model. These terms represent the complete transport equation which is numerically integrated for a period of 2 hr in three-dimensional space.

Initial conditions are based on aerometric and meteorological data acquired in Nashville, Tennessee, during the period 1958-1959. These data are used to establish the three-dimensional distribution of SO_2 and to derive a steady-state condition for the air flow and for the internal emissions of SO_2. A neutrally stable atmospheric condition is specified for a depth of 60 m.

Seven different variations in the model are tested. In all cases, the predicted fields of SO_2 are aligned parallel to the air flow. One case illustrates the important role of vertical diffusion in dispersing SO_2. Another case shows that vertical advection can change local

concentrations of SO_2 by as much as 20 percent of the predicted value. In 2 hr, chemical decay accounts for losses of the predicted value of SO_2 of 10 to 20 percent. It is shown that the correction term dampens out the small scale oscillations of concentration which result from truncation. Predicted concentrations of SO_2 are realistic and compare favorably with observed values.

This study clearly demonstrates that numerical modeling of the diffusion of atmospheric pollutants is feasible, is a potentially fertile domain, and should be pursued in depth. Furthermore, the model offers a high degree of flexibility by permitting frequent changes to be made in the wind direction and speed, in the source strengths, and in the atmospheric stability.

The need for carefully planned and coordinated aerometric and meteorological measurements is stressed. Such observations are mandatory if physically realistic models of atmospheric diffusion are to be developed and tested. Simultaneous sampling of atmospheric pollutants and meteorological conditions is important; this is especially true for the vertical dimension.

ABSTRACT

(4) STUDY OF SAMPLING TECHNIQUES

As a result of statistical analyses the number of sites used for a survey of suspended particulates for Houston was reduced from 28 to 17. Since these sites were eliminated without regard to synoptic situation, this study attempts to determine if their omission could be more significant during certain weather conditions. Data from the survey were grouped according to prevailing wind direction and comparisions were made of the means and variances among the sites using small sampling theory. It was found that three of the sites removed are significantly different from surrounding sites. During periods of southerly winds more "individuality" is observed in the suspended particulate counts throughout the city. Results obtained from the statistical analyses for the reduction of the number of sites may be applicable only during the winter months.

ABSTRACT

(5)(a) MEASUREMENT OF CARBON MONOXIDE

This section is concerned with carbon monoxide measurements made in the vicinity of a freeway interchange in Houston, Texas and in a downtown region of the same city. Freeway monitoring experiments were carried out during the summer of 1969 and 1970. The 1969 freeway experiment utilized 3 vertical carbon monoxide samplers located 15 ft from the freeway and placed 6, 15, and 30 ft above the ground. A fourth sampler was used to determine curbside concentrations of carbon monoxide. The 1970 freeway experiment was performed in the same general area as the 1969 experiment. In this case, however, three of the four samplers were placed in the vertical at the curbside. The fourth was located directly over the center lane of traffic at a height of 25 ft. Carbon monoxide measurements were taken during the daylight hours for all samplers. In both experiments the curbside sampler was allowed to operate all night in order to observe diurnal variations. Statistical correlations were made between carbon monoxide and certain meteorological parameters and between carbon monoxide and traffic. Vertical profiles of carbon monoxide were determined in both experiments to show the variations of carbon monoxide with height. Use was made of Sutton's diffusion equation to study the variability of the vertical exchange coefficient.

An experiment was conducted on March 20 and 21, 1969 to determine carbon monoxide concentrations in the downtown area of Houston, Texas. The experiment utilized the same equipment as in the experiment of July 17-21 1969. The apparatus was set up on the third floor of an office building facing Main Street south of Capitol. Carbon monoxide measurements were taken from a third floor window. Carbon monoxide concentrations were obtained at three levels. Variation was 4 ft below to 4 ft above the horizontal third floor position. The sampler extended 8 ft from the building. Except for some instances of equal readings, the lowest sampler received greater concentrations than the other two samplers.

During the fall of 1970 two studies were made to monitor carbon monoxide concentrations in downtown Houston, Texas. These two experiments, in which daily variations of carbon monoxide were obtained, supplimented early data taken in the spring of 1969. Wind, patterns, both vertical and horizontal, around the building in which the experiments were being conducted were studied. Use was also made of a Barnes infra-red sensor to determine radiation loads coming from various sources surrounding the experiment.

Abstract

(5)(b) THE DISTRIBUTION OF MANGANESE AND BROMINE IN AN URBAN AREA AS REVEALED THROUGH ACTIVATION ANALYSIS

Fifteen high-volume samplers were operated continuously for 24-hr periods in Houston, Texas. Filter papers from one day of sampling were irradiated in a thermal-neutron flux and the resulting radionuclides were identified. Two elements were detected; namely, Manganese (Mn) and Bromine (Br). During one, 24 hr period the concentrations of Mn ranged from 0.02 to 0.56 g m^{-3} while those of Br ranged from 0.04 to 1.09 g m^{-3}. The spatial distributions of these two elements were related to the meteorological conditions. The patterns of concentration appeared to be related to the predominant direction of the wind. The primary source of the Mn is considered to be from industrial effluvia. It is proposed that the Br may have originated as particulates contained in the exhaust gases from motor vehicles.

Abstract

(6)(a) A COMPARISON OF THE SPECTRAL DISTRIBUTION OF SOLAR RADIATION IN A POLLUTED AND A CLEAR AIR MASS

Two spectroradiometer measurements are presented to illustrate differences in the spectrum of sunlight in the 0.5 to 0.75 band. Only two spectral observations are presented, one in an apparently clean, cloud-free air mass, the other under a heavily polluted air mass. Both observations were taken near Houston, Texas, on 12 November 1968, at about 1800 GMT. A 23% loss in the intensity of light is attributed to attenuation by pollution in the atmosphere.

Abstract

(6)(b) Some Aspects of the Form of Houston's Heat Island

This paper describes some preliminary results of an investigation of the dispersion of atmospheric pollutants and the associated pattern of temperatures within the urban area of Houston, Texas. The large-scale meteorological condition at the time of the investigation was one that was conducive to intense atmospheric pollution over the city. Horizontal temperature patterns were determined from data collected during automobile traverses and from temperatures measured at climatological stations. Vertical temperatures were measured during ascents and descents by helicopter. The analysis of the spatial distribution of temperatures disclosed the frequently-observed pattern in which temperatures over built-up areas exceed those measured in open spaces. The variations in the lapse rate of temperature over the urban area are related to variations in the vertical depths of observed layers of atmospheric pollutants.

ABSTRACT

(6)(c) REMOTE SENSING TECHNIQUES

In order to understand more fully the role of air pollution in the Houston area, an airborne survey was conducted on November 18, 1970, over the city and ship channel. The purpose of this flight was to obtain infra-red pictures, ultra-violet measurements, infra-red data, and temperature profiles over the areas of interest. Accurate field measurements were obtained to provide additional information for atmospheric models.

Abstract

(7) A World Survey of Urban Air Pollution

The authorities in urban areas (defined as those with population in excess of one million people) were circulated via a questionnaire to obtain data concerning specific pollutants and sources, among other items. The results, from 55 cities, are given in tabular form and indicate the dominance of sulphur dioxide (90%, 45% serious), particulates (88%, 40% serious), carbon monoxide (82%, 24% serious), oxides of nitrogen (75%, 13% serious), and hydrocarbons (74%, 10% serious) as pollutants. Automobiles and industry dominate as the chief sources but only 18% of the cities report any serious pollution incidents.

(1) CLIMATOLOGICAL STUDIES

Any study of atmospheric processes involving diffusion requires a knowledge of the vertical wind structure. Since Houston currently has no station for observing winds aloft, some method must be employed to estimate the needed wind data.

A solution to this particular problem implies a statistical approach. If a good correlation could be found between the wind distribution at Houston and the wind distribution at some other observing station, a regression technique could be used to estimate the required Houston data. Another possible solution is to correlate the surface winds for Houston (which are available) with the winds aloft so that estimates of the upper winds can be obtained by regression on the surface winds. The purpose of this study is to determine if winds-aloft data for Houston, Texas, can be obtained using vertical and/or horizontal regression methods. The specific objectives were:

1. To investigate the feasibility of establishing monthly regression equations, using the methods of Scott (1956) and Durst (1954), so that estimates of the surface, 500 m, 1000 m, 1500 m, and 2000 m winds at Houston, Texas, can be obtained from their respective winds at Lake Charles, Louisiana (the closest station, geographically, with available wind data).

2. To investigate the feasibility of establishing monthly regression equations, using the same two methods, to obtain estimates of the 500 m, 1000 m, 1500 m, and 2000 m winds from the surface winds at Houston.

3. To evaluate the results obtained using Scott's and Durst's methods for both vertical and horizontal wind regression.

In selecting a winds-aloft observing station for correlation with Houston, the following criteria were considered:

1. Availability of data: Daily winds-aloft punch-card data were available at Lake Charles for the period of interest (1948-1955).

2. Distance between Houston and the observing site: Lake Charles was nearer to Houston than any other observing location. This is an important factor in that Durst (1954) showed that correlation improved as distance between the two stations decreased.

3. Climatological factors which affect wind distribution: Climatologically speaking, the wind distributions at Houston and Lake Charles should be similar. Both stations have the same exposure to the invasions of polar air from the north and northwest, and both (located approximately the same distance from the coast) are subject to the same modifying influences of tropical air from the Gulf of Mexico.

Lake Charles was a logical choice since it best satisfied all the criteria.

Although the differences obtained between use of Ellison's (1954) and Scott's (1956) methods were small, indications are that for elliptically distributed winds Scott's method might be significantly superior to Durst's (1954).

Crutcher (1957, 1962) proposed that geographical location would be decisive in determining wind distribution. He stated that stations located near boundaries between maritime and continental areas and/or regions of strong convergence or divergence should have elliptical distributions.

McDaniel (1967) determined that more than 70% of the wind distributions from the surface to 800 mb (13 stations, encompassing Texas, New Mexico, Oklahoma, Arkansas, and Louisiana) were elliptical.

For the above reasons, it was decided to compare the results obtained using Scott's (1956) and Durst's (1954) methods to determine if there was any significant difference between the two.

In order to accomplish the proposed objectives of this study, winds-aloft data for Houston and Lake Charles were required. Punch-card data were available for both stations covering the period January 1948 to June 1955 from the National Weather Records Center, Asheville, North Carolina. Each data card contains station indentifier, year, month, day, time, wind direction (16 points of the compass), and wind speed in mps for every 500 m from the surface to 11,000 m. The data are composed of observations taken by RAWIN, RABAL, and PIBAL and the usual observation times are either 0400Z, 1000Z, 1600Z, and 2200Z or 0300Z, 0900Z, 1500Z, and 2100Z (depending upon the year in which the observations were taken).

Durst's (1954) results indicate that there is very little seasonal variation in the horizontal stretch correlation coefficient (r_x) for a given distance, with the summer values being slightly lower than the winter value. This study reveals (see Figure 1) that there is a distinct summer minimum which is from 0.07 to 0.25 smaller (depending on the level) than the winter maximum value. Figure 1 was constructed by taking monthly r_x values for each level combining the monthly values into seasonal values ($\bar{r}_x$), and plotting the resulting $\bar{r}_x$, for each level, against season. Iso-level lines were then drawn connecting $\bar{r}_x$ values for the four seasons. The usual seasonal delineations were used, i.e., December, January, and February for winter, etc..

Most of the r_x values are greater than 0.70. According to Brooks and Carruthers (1953), when the population correlation coefficient is large, the sampling distribution (distribution of r_x in this case) is far from being normal. This means that we should not combine monthly values of r_x using a simple arithmetic average. Fisher's z' transformation was devised for this purpose and is given by

$$z' = \tfrac{1}{2}\left[\ln(1+r_x) - \ln(1-r_x)\right] \quad .$$

Fisher showed that z' is nearly normally distributed and arithmatic averaging of this parameter is meaningful. Values of correlation coefficients computed from two or more sets of data can be combined using the above transformation provided that it can be assumed that the different sets of data are samples from the same population. The most efficient way is to convert the values of r_x to values of

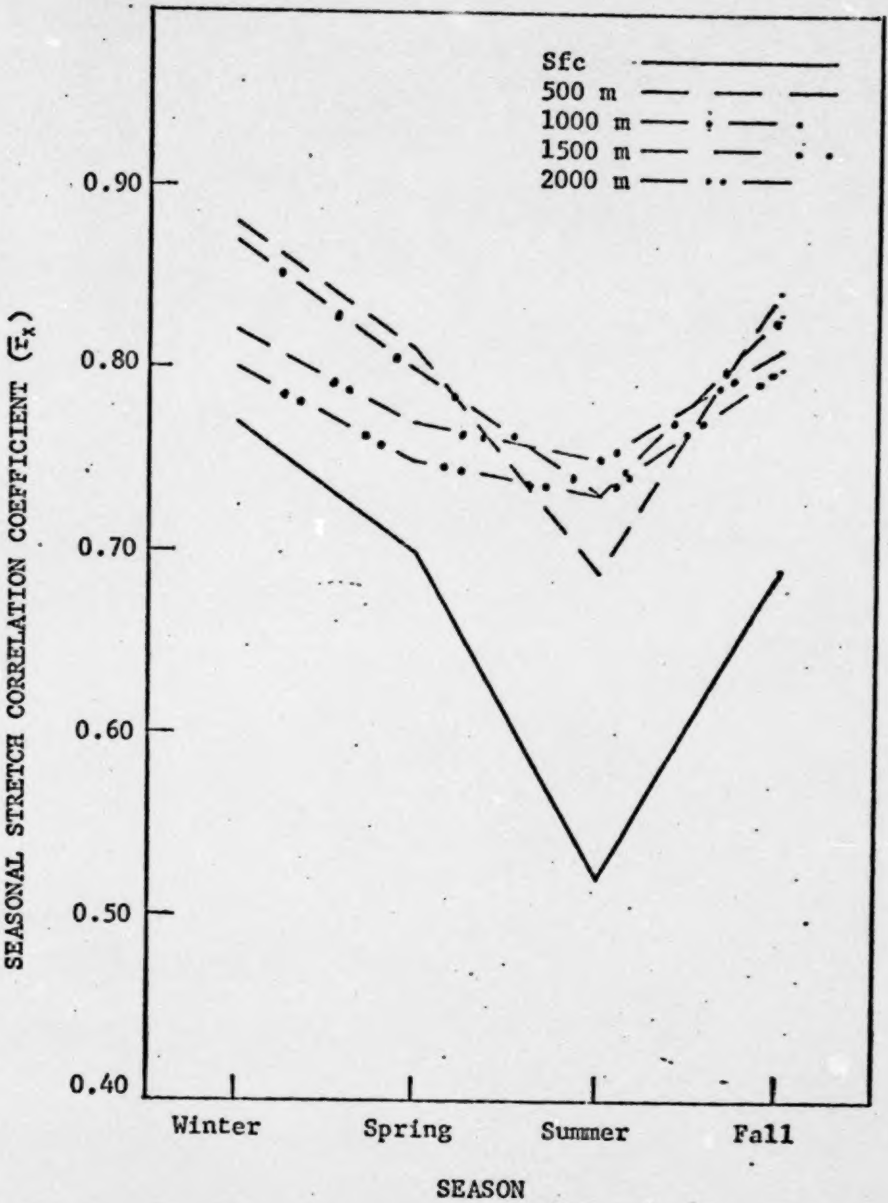

Fig. 1. Variation with season of stretch correlation coefficient ($\bar{r}_x$) between Houston and Lake Charles.

z', find a weighted mean of the z''s, and convert back to r_x again. This is the procedure that has been used in combining correlation coefficients in this study.

To appreciate what we may infer from the summer minimum of the correlation coefficients, we should convert the $\bar{r}_x$ values (shown in Figure 1) to $\bar{r}_x^2$ values (since $\bar{r}_x^2$ is defined as the ratio of the explained to the total variance). This means, for example, that during the winter at 500 m 77% of the variance in the Houston wind can be explained by regression on the Lake Charles wind, while during the summer only 48% can be accounted for. The above percentage values were obtained by entering the abscissa of Figure 1 at winter/summer, proceeding vertically until intersecting the slanting line representing 500 m, then proceeding left, horizontally, until intersecting the ordinate at 0.88/0.69. These $\bar{r}_x$ values were converted to $\bar{r}_x^2$ and then multiplied by 100 to obtain 77%/48%. The summer minimum probably is due to a change from the influence of large-scale, highly-organized, winter weather systems (cyclones and anticyclones) to that of the small, local weather phenomena (drainage winds, seabreeze, etc.) typical of summer.

Durst's (1954) results also indicate that, for a given distance, r_x is a maximum at 3000 ft (the lowest datum level that he used) and decreases to a minimum at 300 mb. The results of this study show (see Figure 2) that the maximum occurs at approximately 2200 ft for all seasons except summer. The maximum is most pronounced

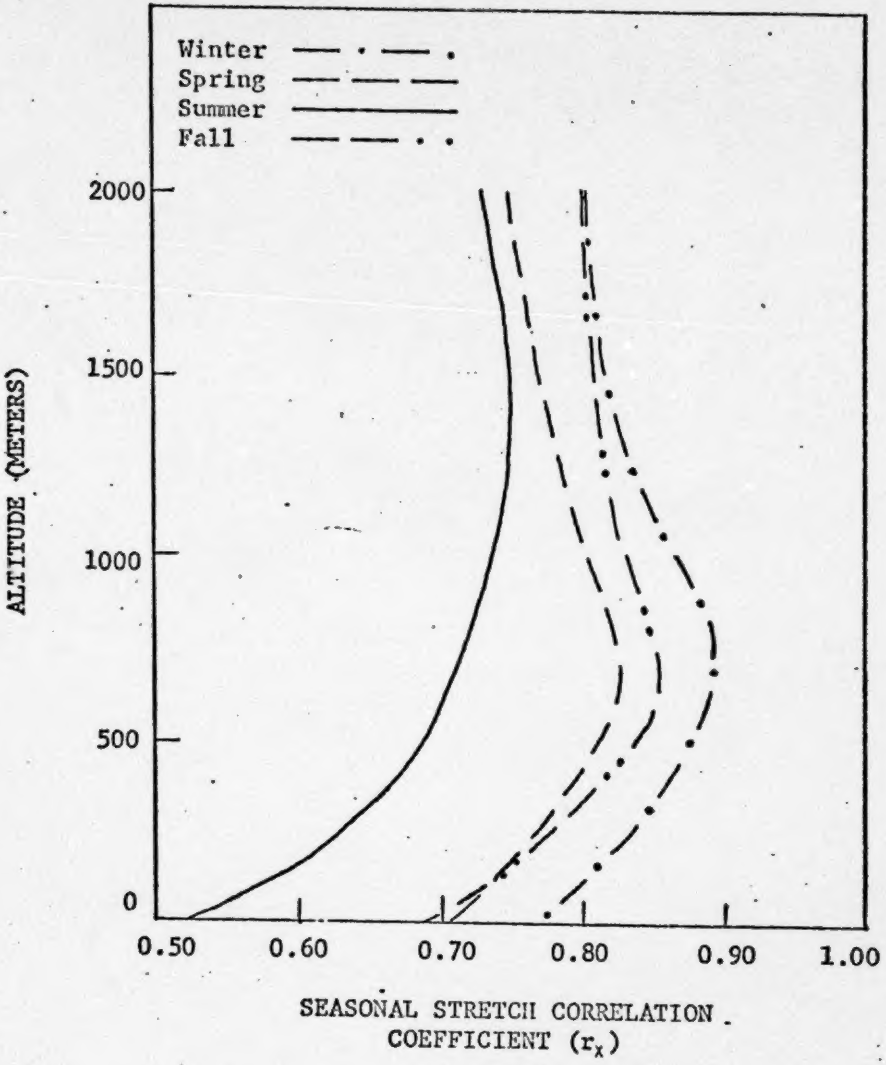

Fig. 2. Variation with altitude of stretch correlation coefficient ($\overline{r}_x$) between Houston and Lake Charles.

during the winter. Figure 2 also shows that above 1500 m $\bar{r}_x$ changes very little with height. The same $\bar{r}_x$ values were used in constructing both Figures 1 and 2. In Figure 2, r_x values were plotted against altitude and iso-seasonal curves were drawn connecting the different levels.

It seems that the values of r_x obtained in this study are in good agreement with values obtained in earlier works. It also can be seen by examining Figure 1 (using $\bar{r}_x{}^2$ that from 48% to 77% of the wind variance at Houston can be explained by correlation with the winds at Lake Charles (depending on season and level). The above percentage values do not pertain to the surface winds. Since Houston International Airport and Ellington AFB can supply the surface wind data, we need not be concerned with regressing the Houston surface wind on the Lake Charles surface wind.

It is obvious, after comparing the r_x values (obtained by correlating Houston winds at level x with those at Lake Charles) with the $r_{i,j}$ values (obtained by correlating Houston winds at level x with the surface wind at Houston), that regressing the Houston lower level winds on the corresponding winds at Lake Charles will give better results than regressing the Houston lower level winds on the Houston surface winds. This is shown more explicitly in Table I.

TABLE I. Comparison of r_x values obtained by DIST (D) with $r_{i,j}$ values obtained by VERT (V).

Lower Level "i"	Upper Level "j" (m/ft)	Jan.		Apr.		Jul.		Oct.	
		D	V	D	V	D	V	D	V
Surface	500/1640	0.90	0.79	0.80	0.83	0.71	0.67	0.83	0.76
Surface	1000/3280	0.80	0.68	0.84	0.70	0.77	0.48	0.84	0.59
Surface	1500/4920	0.85	0.61	0.81	0.62	0.78	0.33	0.81	0.47
Surface	2000/6560	0.82	0.52	0.79	0.57	0.77	0.26	0.82	0.42

The most significant difference occurs at the 2000-m level in July. The distance regression technique indicates that 59% of the variance in the Houston 2000-m wind can be explained. The altitude regression method indicated that only 7% of the variance in the Houston 2000-m wind can be explained. The superiority of the distance regression method is obvious at all levels for all seasons. In any regression scheme there is always a certain amount of scattering of individual observations about the mean. Even when two distributions exhibit a high degree of correlation there is still a good chance that several of the individual values are drastically different from the mean. It should be of interest to determine the scatter of the Lake Charles wind when the Houston wind is from a particular direction.

According to McKee (1958), the most unfavorable air pollution pattern for Houston results when the wind is from the east or east-northeast. The question is, when the Houston wind is from one of the above two directions is the Lake Charles wind direction confined to certain limits or is it likely to wander over the compass rose? If there is a tendency for the latter, the derived regression equations will lose much of their effectiveness.

In an attempt to determine scatter, an additional program segment was added to DIST. Each time that the wind direction at Houston was from the east-northeast, east, or east-southeast the wind direction at Lake Charles was noted (this was accomplished for all levels and for all months). The results show little scattering.

TABLE II. Scattering of Lake Charles wind direction when Houston wind direction is from east-northeast, east, and east-southeast.

		Lake Charles Direction (16 point compass)							
		% of Obs. That Fell Within 3 Compass Points Either Side of the Centroid				% of Obs. That Fell More Than 90 Deg Either Side of the Centroid			
Level	Houston Direction	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct
Sfc	03 (ENE)	96	92	100	97	4	8	0	3
	04 (E)	89	83	87	89	5	15	13	9
	05 (ESE)	89	71	80	84	5	20	12	8
500m	03	96	95	88	100	4	5	6	0
	04	100	93	95	94	0	0	5	4
	05	90	88	94	99	10	8	3	0
1000m	03	92	91	94	98	8	4	0	0
	04	90	91	97	96	10	4	3	2
	05	100	87	86	96	0	13	11	2
1500m	03	91	100	90	87	9	0	5	8
	04		90	89	98		5	11	2
	05		79	87	94		8	11	6
2000m	03		100	97	94		0	0	6
	04		100	82	96		0	14	2
	05		78	84	96		12	12	2
Avg.		93	89	90	94	5	7	7	3
Over-all Average		91				6			

The results are shown in Table II. It was determined that when the Houston wind direction was from the east-northeast, east, or east-southeast, more than 91% (over-all average) of the Lake Charles observed wind directions fell within three compass points (assuming a 16-point compass) of either side of the centroid of the Lake Charles observations. For our purposes the centroid is defined as the compass point closest to the mean of the observed wind directions. In addition, fewer than 6% of the remaining observations fell more than 90 deg from either side of the centroid. Another important result which should be noted is that in nearly all cases the centroid of the Lake Charles observed wind directions fell within two compass points of either side of the Houston wind direction being considered. It is assumed that the other months would show similar direction scattering.

Scattering of wind speed is not as critical as direction scattering; however, this also was investigated. Arbitrary speed categories of 1 to 4 mps, 5 to 9 mps, 10 to 14 mps, and 15 mps plus were established. Each time that the Houston wind speed was observed to fall into one of the above categories, the wind speed at Lake Charles was noted. The results showed nominal scattering.

APPENDIX

Detailed Solution of Derived Regression Equations

Let us suppose that the observed 500-m wind at Lake Charles on January 8, 1975 at 1200Z is from the southeast at 5 mps and we wish to estimate the 500-m wind at Houston for the same time using the regression equations derived in this study. Those equations, in their simplest form, are

$$v_1 = \bar{v}_1 + E_{11} (Y_1 - \bar{Y}_1)$$

and

$$v_2 = \bar{v}_2 + E_{11} (Y_2 - \bar{Y}_2) \quad .$$

v_1 is the predicted Houston east (+) or west (-) wind component for a given month and level.

$\bar{v}_1$ is the average Houston east (+) or west (-) wind component for a given month and level.

E_{11} is the Durst regression coefficient for a particular month and level. Using Table E1 (January, 500 m), we get 0.94.

$\bar{Y}_1$ is the average Lake Charles east (+) or west (-) wind component for a given month and level.

v^2 is the predicted Houston north (+) or south (-) wind component for a given month and level.

$\bar{v}_2$ is the average Houston north (+) or south (-) wind component for a given month and level.

$\bar{\Psi}_2$ is the average Lake Charles north (+) or south (-) wind component for a particular month and altitude.

Ψ_1 and Ψ_2 are the east (+) or west (-) and north (+) or south (-) components of the observed Lake Charles wind. In this example, the observed wind is from 135 degrees at 5 mps. This wind has to be converted to components in order to obtain Ψ_1 and Ψ_2.

Table AI was used to convert the observed wind into components. The Lake Charles observed wind direction and speed will be referred to as θ and V_L, respectively.

Table AI Determining components of the observed Lake Charles wind (Ψ_2 and Ψ_1),

If θ is (inclusive)	Ψ_2 is	Ψ_1 is
001 to 090 degrees	$V_L \sin(90-\theta)$	$V_L \sin\theta$
091 to 180 degrees	$-V_L \sin(\theta-90)$	$V_L \sin(180-\theta)$
181 to 270 degrees	$-V_L \sin(270-\theta)$	$-V_L \sin(\theta-180)$
271 to 360 degrees	$V_L \sin(\theta-270)$	$-V_L \sin(360-\theta)$

Since the observed Lake Charles wind is from 135 degrees at 5 mps, we extract, from Table AI,

$$\Psi_2 = -V_L \sin(\theta-90)$$

and

$$\Psi_1 = V_L \sin (180-\theta) \quad ,$$

or

$$\Psi_2 = -5.0 \sin (045)$$

and

$$\Psi_1 = 5.0 \sin (045) \quad .$$

Substitution in the above equations for sin (045), 0.707, gives

$$\Psi_2 = -3.54 \text{ mps}$$

and

$$\Psi_1 = 3.54 \text{ mps} \quad .$$

Now we must extract the mean winds for Houston and Lake Charles (January, 500 m) from Table E1 and convert them into components. Using the same procedure that we employed to obtain Ψ_2 and Ψ_1, we get

$$\bar{v}_2 = -3.34 \text{ mps} \quad ,$$

$$\bar{v}_1 = -0.65 \text{ mps} \quad ,$$

$$\bar{\Psi}_2 = -2.54 \text{ mps} \quad ,$$

and

$$\bar{\Psi}_1 = -1.83 \text{ mps} \quad .$$

Table AII. Determining resultant Houston wind direction, Φ.

	Φ equals
If υ_2 and υ_1 are positive	A
If υ_2 is negative and υ_1 is positive	180-A
If υ_2 and υ_1 are negative	180+A
If υ_2 is positive and υ_1 is negative	360-A
If υ_2 is positive and υ_1 is zero	360
If υ_2 is zero and υ_1 is positive	090
If υ_2 is negative and υ_1 is zero	180
If υ_2 is zero and υ_1 is negative	270

and

$$A = \tan^{-1} \left\{ \left| 3.79/(-4.28) \right| \right\} ,$$

$$= \tan^{-1} (0.88) ,$$

$$= 041 \text{ deg} .$$

Therefore, according to equation (H13),

$$\Phi = 139 \text{ deg} .$$

To obtain the resultant Houston wind speed, V_H, we use

$$V_H = (\upsilon_1^2 + \upsilon_2^2)^{\frac{1}{2}} ,$$

$$= \left[(3.79)^2 + (-4.28)^2 \right]^{\frac{1}{2}} ,$$

Now, substituting all known values into equations (A1) and (A2), we obtain

$$\nu_1 = -0.65 + 0.94\ [3.54 - (-1.18)]$$

and

$$\nu_2 = -3.34 + 0.94\ [-3.54 - (-2.54)] \quad ,$$

or

$$\nu_1 = 3.79 \text{ mps}$$

and

$$\nu_2 = -4.28 \text{ mps} \quad .$$

To obtain the predicted Houston wind we must convert the resultant components (ν_1 and ν_2) into wind direction and speed. Table H2 was used to obtain the predicted Houston wind direction, Φ.

In the table on the page following, $A = \tan^{-1} \left\{ |\nu_1/\nu_2| \right\}$; i.e., A can be extracted from trigonometric tangent tables entering with the absolute value of ν_1/ν_2.

In this example, ν_2 is negative and ν_1 is positive; thus, using Table AII,

$$\Phi = 180 - A$$

$$= (14.36 + 18.32)^{\frac{1}{2}}$$

$$\doteq 5.72 \text{ mps}$$

The predicted 500 m wind at Houston on January 8, 1975 at 1200 z has now been computed and is 139 deg at 5.7 mps.

The predicted Houston wind for any month and level can be computed from the corresponding observed Lake Charles wind by solving equations (AI) and (AII) and using the parameters extracted from the appropriate tables.

In using the above regression equations, one must remember that the results obtained are subject to deviation. When the wind at Lake Charles (January, 500 m) is from the southeast at 5 mps, the actual wind Houston will not always be from 139 deg at 5.7 mps, but will deviate around that value. The standard vector error, f, gives a measure of that deviation. In this case f is 5 mps. This means that 63% of the time the terminus of the actual wind vector at Houston will fall within a circle of radius f with origin at the head of the vector 139 deg and 5.7 mps.

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(2) AREAL AND TEMPORAL DISTRIBUTION OF POLLUTANT EMISSIONS FROM VEHICLES IN HOUSTON

Introduction

The location of sources of air pollution and their strengths of emission are basic to the evaluation of the diffusive transport of these contaminants by the atmosphere. If the geographical distribution of the pollution sources and the intensity of these sources is known, then the atmospheric concentration of the pollutants depends on the vertical variation of temperature and the mean velocity and turbulent characteristics of the wind. The variation of temperature in the vertical essentially determines the depth of the atmosphere into which the pollutants will be diluted while the wind velocity and turbulence determine horizontal transport and dispersal. The manner in which the concentration of pollutants varies with the source distribution, their emission features and the meteorological conditions is an extremely complex one. To make this problem tractable, one can describe the relationship between the mean concentration of pollution, the statistical characteristics of the turbulence and the mean wind velocity. The development of a mathematical model of diffusion is one of the objectives of the current research being conducted by the Department of Meteorology at Texas A&M University.

The utility of a model of diffusion is enhanced if predictions of pollutant concentrations can be made at both the micro- and mesoscales of motion. A mesoscale model of three dimensions was developed by

Randerson (1968) (see section 3 of the report) which predicts the diffusion of sulfur dioxide over a moderately large urban area. This model was begun prior to the initial collection of the primary data from Houston. Atmospheric dispersion at the microscale has been studied by Thomas (1970) (see section 5, this report). In this work he considered variations of the diffusion of carbon monoxide from vehicular traffic near a freeway interchange and in the central business district of Houston. Thomas found that solutions to the atmospheric diffusion equation could be used to predict reasonable values of CO close to the vehicular sources.

The predicted pattern of pollutants at the mesoscale over Houston can suggest areas of study to measure the effect of microscale processes. If the mesoscale pattern is viewed as a smoothed version of many microscale patterns, then it may be possible to assess the magnitude of any particular microscale process by considering this process as the cause of a local departure from the predicted mesoscale pattern. In order to use Randerson's model for Houston, it is necessary to describe the mesoscale patterns of emissions of selected pollutants as functions of geographical location and time.

The variation of pollutant emissions from vehicles is considered here. In the context of this report we have not considered the emissions from the use of fuels by commercial, industrial and residential sources nor the emissions occuring during industrial processes. A large amount of data, both direct and indirect, were collected to determine the amounts of pollutants emitted by such stationary sources. This effort was conducted at the same time as the one to determine emissions from moving sources. During the course of the period of data collection, we learned that the National Air Pollution Control Administration (NAPCA) was calculating an emission inventory of the eight-county Houston-Galveston area as one of the preliminary steps in the establishment of air-quality criteria for this air basin. Some of our preliminary work on vehicular traffic was furnished to the NAPCA for use in this inventory. Since our preliminary emission data for stationary sources was generally consistent with the NAPCA report, we concentrated most of our further activities on the inventory of emissions from vehicles.

Analysis of Basic Data

The area for which vehicle emissions were computed is a 760 mi^2, rectangular one including the built-up portion of the city of Houston and the industrial-residential part of eastern Harris County (see Fig. 1). The lengths of the boundaries of the rectangle are twenty miles on the eastern and western edges and thirty eight miles along the northern and southern edges. A grid system made up of lines at one-mile intervals was drawn on a map of this area and the mile-square areas bounded by the grid lines served as computational zones. A spacing of one mile is suitable for analysis at the mesoscale.

Nature of emissions from individual vehicles. The emissions of pollutants from vehicles are primarily those typical of the combustion of fossil fuels used, gasoline or diesel, will affect the amounts and quantities emitted. Carbon monoxide, hydrocarbons, nitrogen oxides,

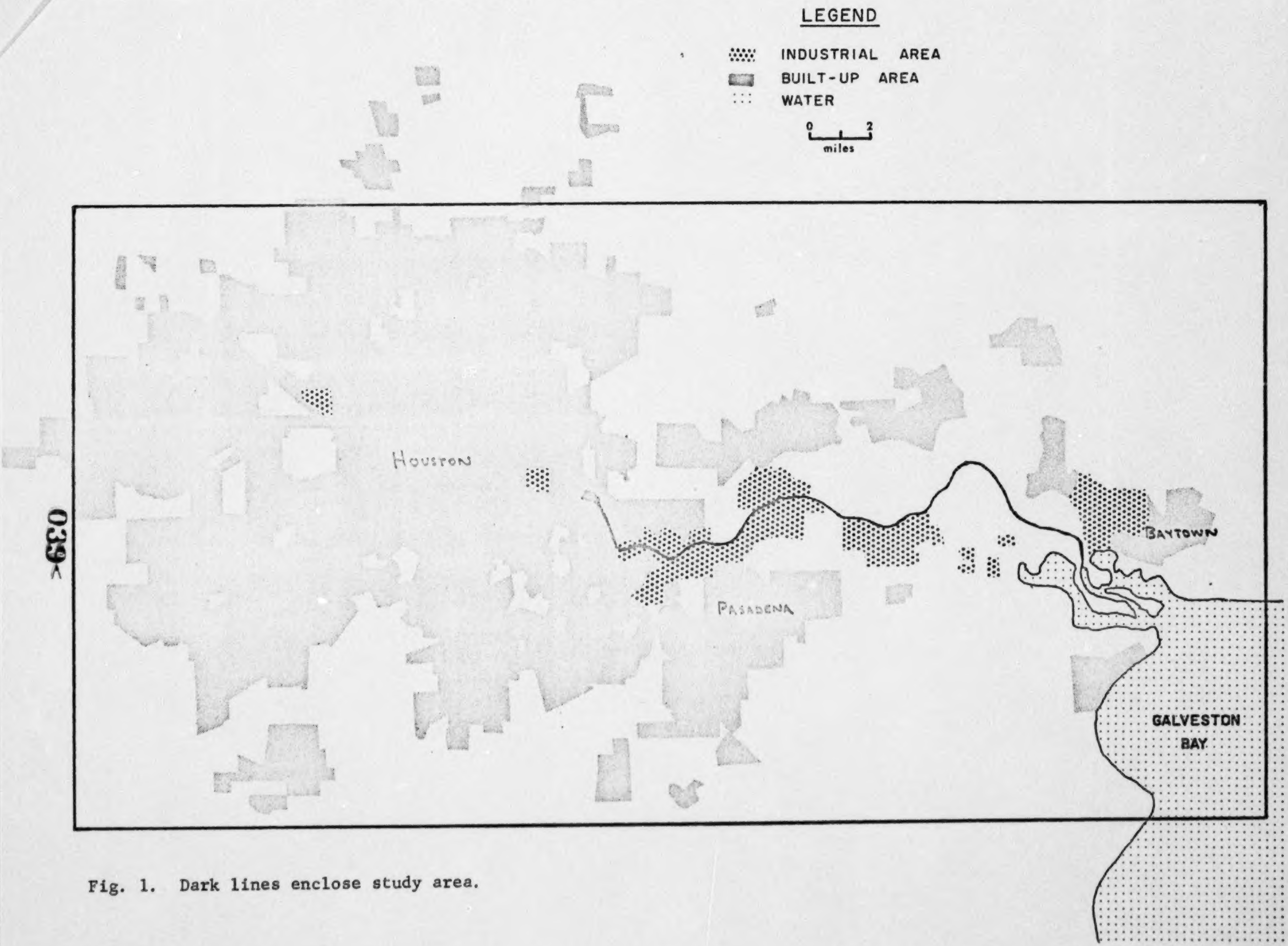

LEGEND
INDUSTRIAL AREA
BUILT-UP AREA
WATER
0
2
miles
HOUSTON
PASADENA
BAYTOWN
GALVESTON BAY

Fig. 1. Dark lines enclose study area.

and particulate matter (carbon particles, lead, chlorine, bromine, phosphorus, and motor oil) are the predominant pollutants. The major portion of vehicular pollutants enter the atmosphere from the exhaust system, however about one-half of the hydrocarbon losses from automobiles are due to evaporation from carburetor vents, the crankcase and the fuel tank. The evaporative losses occur when a vehicle is not operating as well as during the operating mode.

For diesel-burning vehicles, emissions of carbon monoxide and hydrocarbons are lower, but emissions of nitrogen oxides, aldehydes, oxides of sulfur, organic acids and particulates are greater than emissions from gasoline engines.

Controlled and uncontrolled emissions. Automotive emissions can be reduced by altering the engine design or by adding exhaust, crankcase and fuel evaporation controls. Control systems for diesel exhaust emissions have not been developed (Duprey, 1968).

Devices to control crankcase emissions of hydrocarbons have been installed on new automobiles since 1963. Rose (1965) has found that these devices are approximately 90% effective on new vehicles, but deterioration in effectiveness is noticed after several thousands of miles of travel (Lemke et al., 1969). Controls to reduce hydrocarbons and carbon monoxide emissions in the exhaust system have been installed on new vehicles since the 1968-model year. Tests (Mc Michael et al., 1967) made at low altitudes of these exhaust of these exhaust controls indicate that they reduce hydrocarbons by 35%, reduce carbon monoxide by 67%, but increase the emission of nitrogen oxides by 26%. The increase of oxides of nitrogen is the result of the increased air/fuel ratio achieved by the 1968 exhaust controls. Thus, while reducing the hydrocarbon and carbon monoxide emissions, the increased volumes of air improved combustion and enhanced the formation of nitrogen oxides. The effectiveness of the controls on evaporative emissions is unknown.

Calculations of the areal variations of vehicular traffic. Since we are concerned with mobile sources of pollution it is necessary to determine the geographical distribution of these sources during the course of a suitable time interval (say 24 hours). Once the geographical variation is known, the temporal changes within this larger time interval can be ascertained.

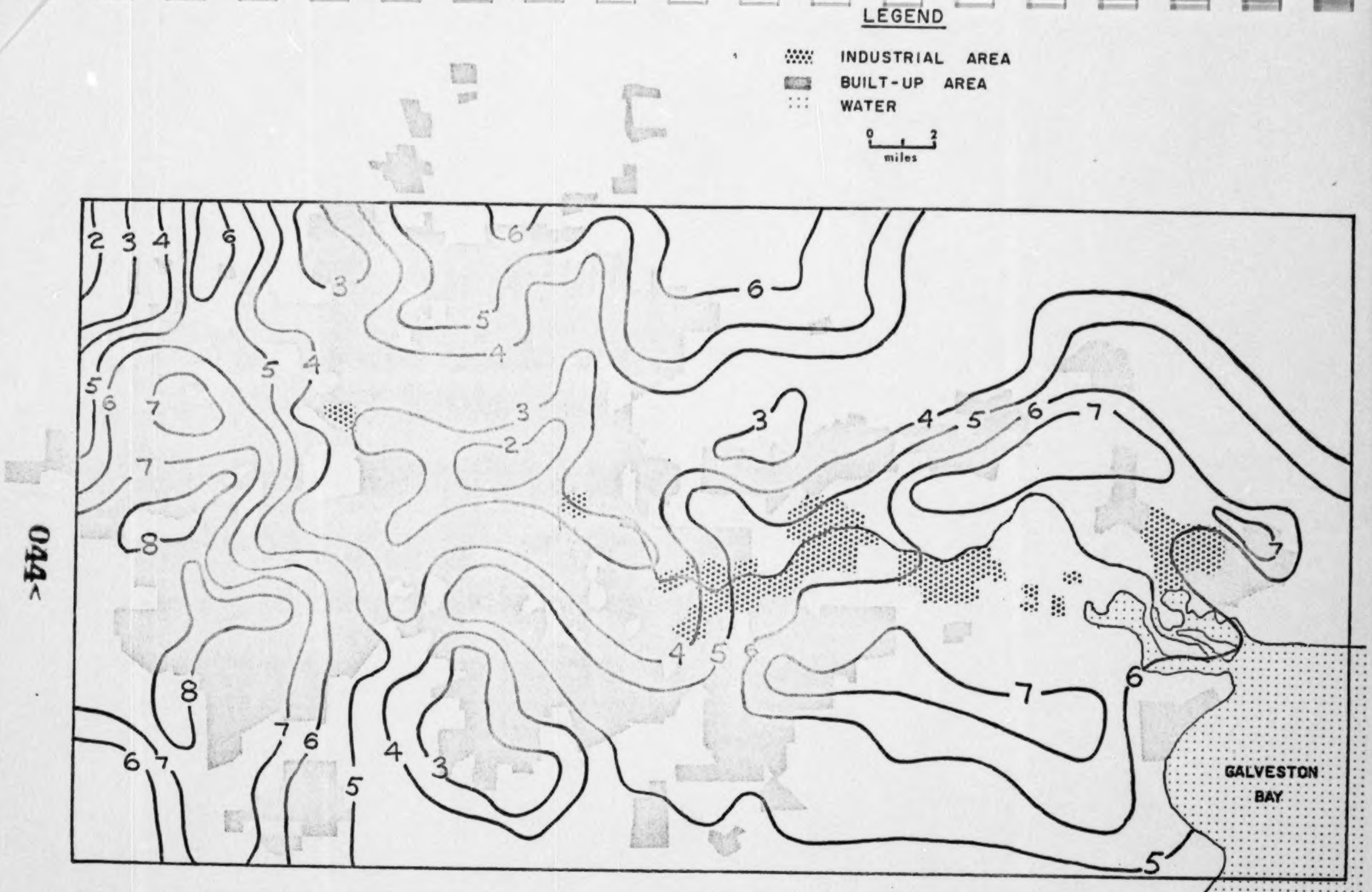
The one-mile square grid zones mentioned above were the bases for the computation of exhaust emissions. For the purposes of calculating the amounts of pollutants emitted within one of these zones, the fuel consumption within this area must be known. By the use of suitable parameters (usually termed "emission factors") the emission of certain pollutants as a function of fuel consumption can be calculated. Since the amounts of pollutants vary with type of fuel mixture, driving speed, performance level of vehicle and meteorological conditions, an "average" emissions factor is used which reflects the results of many tests of vehicle emissions.

The fuel consumption on the streets within one zone will, like the rates of pollutant emission, vary with vehicle speed, engine performance and characteristics of the individual driver. A useful proxy for fuel consumption is the unit of a vehicle-mile. The aggregate of this unit is very useful when total amounts of fuel consumption by all vehicles in a zone are required since it is a measure of both the number of vehicles and the distance traveled. The vehicle-mile does not account for variations in fuel consumption with changes in speed. A more precise measure of aggregate fuel consumption would incorporate the effect of an "average" speed appropriate to the vehicles traveling in one mile-square zone.

The total movement of vehicular traffic within the study area (expressed in units of vehicle-miles) may be regarded as traffic on major and minor streets. The category of major streets will be used to designate those thoroughfares for which daily counts of vehicles are available. Included in this category are limited-access highways (freeways), arterial and collector streets. The approximate combined length of these major streets is over one thousand miles and the average spacing is 1.3 miles. Vehicle counts at 1,320 locations were obtained from the cities of Houston, Pasadena and West University Place and from the Texas Highway Department. The dates of collection varied, but latter 1967-nearly 1968 is a representative date. The spacing of the collection locations was fairly uniform over the built-up area. The category of minor streets (often termed "local") represents those neighborhood streets for which no daily counts were available.

The calculation of vehicle-mileage on the major streets within a grid zone consisted of forming the product of the length of each street within the zone and the vehicle count appropriate to that street. Often segments of these streets had varying counts over the length within the zone. In this case the count for each segment was multiplied by the segment length. The combined vehicle mileage for each of the 760 zones was recorded for later combination with the vehicle-mileage computed for the minor streets in that particular zone.

To estimate the vehicle mileage on uncounted (minor) streets within a grid zone, a technique was developed that combined information from areal population estimates and the Houston-Harris County Transportation Plan (1964). This latter study is one of many area transportation studies conducted under the auspices of the U.S. Bureau of Public Roads. One of the items of information collected during these studies is the average number of trip terminals (origins and destinations) per dwelling unit that occur in 24 hours within the different zones that constitute the study area. Figure 2 shows the areal pattern for the Houston area. If we know the distance traveled during each of these terminal movements before merging with traffic on a counted street, then the aggregate of the products of the zonal trip terminals and distance traveled will be a measure of vehicle mileage on minor streets. Population and housing estimates are used to determine the zonal total of trip terminals. This total is the product of the number of dwelling units in a zone and the average number of trip terminals per dwelling unit. Because of the complexity of estimating the distance traveled



LEGEND
▨ INDUSTRIAL AREA
▨ BUILT-UP AREA
∴ WATER
0 2
miles
GALVESTON BAY
2
3
4
6
3
5
4
6
5
4
6
3
2
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7
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5

Fig. 2. Isolines of daily trip terminals (origins and destinations) per dwelling per square mile.

by each terminal movement within a mile-square zone, an average distance of travel per zone was used. This average distance was based on interviews with drivers in Houston and an examination of the street pattern within each zone. The average for all zones approximately 0.5 mi. This is in good agreement with data from other cities (Creighton et al., 1960) It appears that the similar forms of U.S. cities has resulted in a similar spacing between arterials.

The vehicle mileage computed for major and minor streets was summed for each grid zone to obtain the zonal total. The areal total, resulting from the summation of all grid zones was 13.8×10^6 vehicle-miles of travel in 24 hours. This figure, appropriate to the 1967-68 data, was consistent with the figure given by the Houston-Harris County Transportation Plan. Projections by this study indicate that the 1970 traffic volume for this area is approximately 17.0×10^6 vehicle-miles per 24 hours. In 1968 daily traffic flow on counted streets amounted to 12.8×10^6 vehicle-miles (92.8% of the area total) and volume on uncounted streets was 995.4×10^3 vehicle-miles (7.2%). Since we were using vehicle mileage as a proxy for fuel consumption and pollutant emissions, the total mileage in one zone was divided by the total for the 760 mi^2 area in order to obtain a relative value. These values could then be multiplied by the total fuel consumption or total pollutant emissions to obtain zonal values of these respective quantities. Figure 3 shows the isolines of constant traffic density in units of percent of the area total. These isolines were obtained by a scalar analysis of the individual zonal values. The zonal fraction

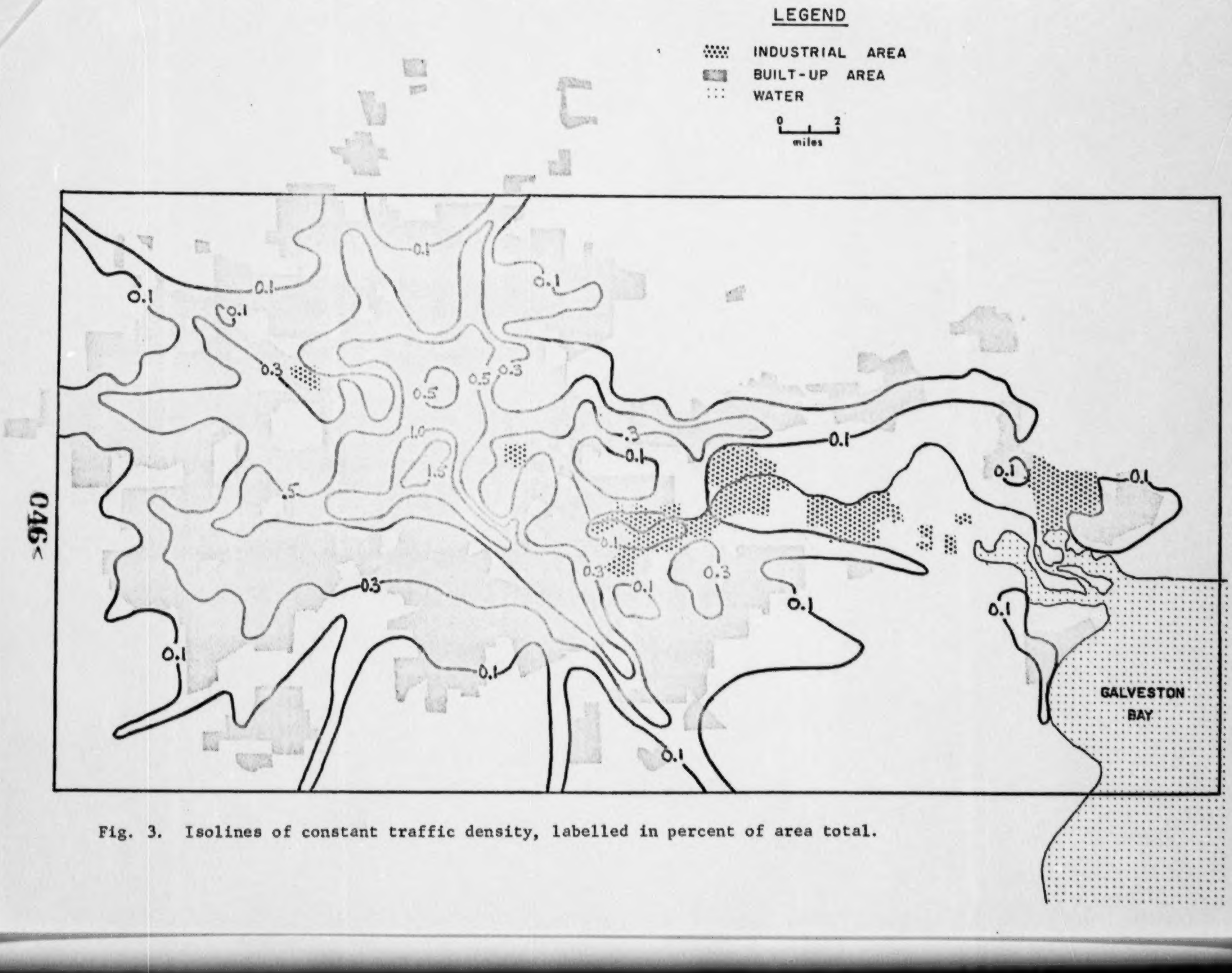

LEGEND
▩ INDUSTRIAL AREA
▨ BUILT-UP AREA
∴ WATER
0 2
miles
GALVESTON BAY
0.1
0.3
0.5
1.0
1.5
.3
.5

Fig. 3. Isolines of constant traffic density, labelled in percent of area total.

of the area total was assigned to the centroid of each grid zone for the purpose of this analysis. While the volume of traffic has increased since the collection of these traffic counts, it appears that the relative pattern (percentage lines) has not changed accordingly. The opening of a new traffic artery, such as a freeway, usually produces a slight shifting in these lines.

Since the traffic counts include both gasoline and diesel-burning vehicles, the vehicle mileage determined by the above procedure must be divided into the appropriate fractions when estimating emissions of pollutants. Most of the vehicle traffic using diesel oil as a fuel are confined to a few major arterials. Accordingly, the grid zones through which these selected arterials passed were apportioned on a diesel/gasoline ratio equal to the ratio of diesel-consuming trucks and buses to automobiles (approximately 2%)

Emission factors. Average relationships between exhaust emissions and traffic characteristics (emission factors) have been determined by various groups (Duprey, op. cit.). Table 1 shows a recent compilation of uncontrolled emissions of pollutants from both gasoline and diesel vehicles as functions of certain traffic parameters. The emission factors for carbon monoxide and hydrocarbons tend to decrease with increasing speed and they vary with the portion of the engine operating cycle. In the absence of precise data on vehicle speeds, we assumed an average speed of 25 miles per hour in each zone. The data in Table

TABLE 1 EMISSION FACTORS

	Automobile Exhaust			Diesel Engines
Type of emission	pounds/1000 vehicle-miles	pounds/1000 gallons of gas	pounds per vehicle-day	pounds/1000 gallons of diesel
Aldehydes (HCHO)	0.3	4	0.007	10
Carbon monoxide	165.0	2300	4.160	60
Hydrocarbons (C)	12.5	200	0.363	136
Oxides of nitrogen (NO_2)	8.5	113	0.202	222
Oxides of sulfur (SO_2)	0.6	9	0.016	40
Organic acids (acetic)	0.3	4	0.007	31
Particulates	0.8	12	0.022	110

1 are based on this speed. Emissions of the remaining pollutants listed in Table 1 are not dependent on vehicle speed, but the emission of oxides of nitrogen is dependent of the air/fuel ratio.

Evaporation of hydrocarbons from fuel tank, the crankcase and carburetor were determined by using the following emission factors:

Carburetor and fuel tank	76 lb/10^3 gallons of fuel
Crankcase	103 lb/10^3 gallons of fuel

Calculation of the areal variation of emissions. Within the assumptions regarding vehicle-mileage as a proxy for fuel consumption, the isolines of constant traffic density in Figure 3 may be regarded as isolines of constant daily fuel consumption or isolines of constant daily pollution emission from exhausts. If the amount of fuel consumed within the entire study area in a 24-hour period is known, then this figure can be used to convert the percentage lines to fuel-consumption lines. The use of the emission factors from Table 1 then could be used to convert the fuel-consumption lines to pollutant-emission lines. We did not have data on the annual consumption of fuels within the study area and, as a consequence, we used the column of Table 1 that shows the average emission of the various pollutants from automobiles as a function of vehicle-mileage. In order to determine the amounts of pollutants emitted from diesel-burning vehicles, we assumed a rate of fuel consumption of one gallon per 5.1 miles of travel per vehicle (Ozolins and Smith, 1966). This conversion factor allowed us to use the last column in Table 1 to calculate the emissions from diesel-vehicles in those grid zones where most of their daily mileage occurs.

Figures 4,5,6,and 7 show the areal pattern of the daily emission of carbon monoxide, hydrocarbons, oxides of nitrogen and particulates, respectively. The magnitude of the units reflect emissions with no control systems and the 1968 traffic data. Thus, within the limits of accuracy of the assumptions regarding the applicability of average emission factors, these figures can be interpreted as upper limits of pollutant emissions. The actual figures may be somewhat lower depending on the efficiency of the control devices. The efficiency of such devices is under examination and, in addition, the ten-year replacement cycle of the automobile population indicates that 1985 will be the earliest date for total implementation of control systems meeting the

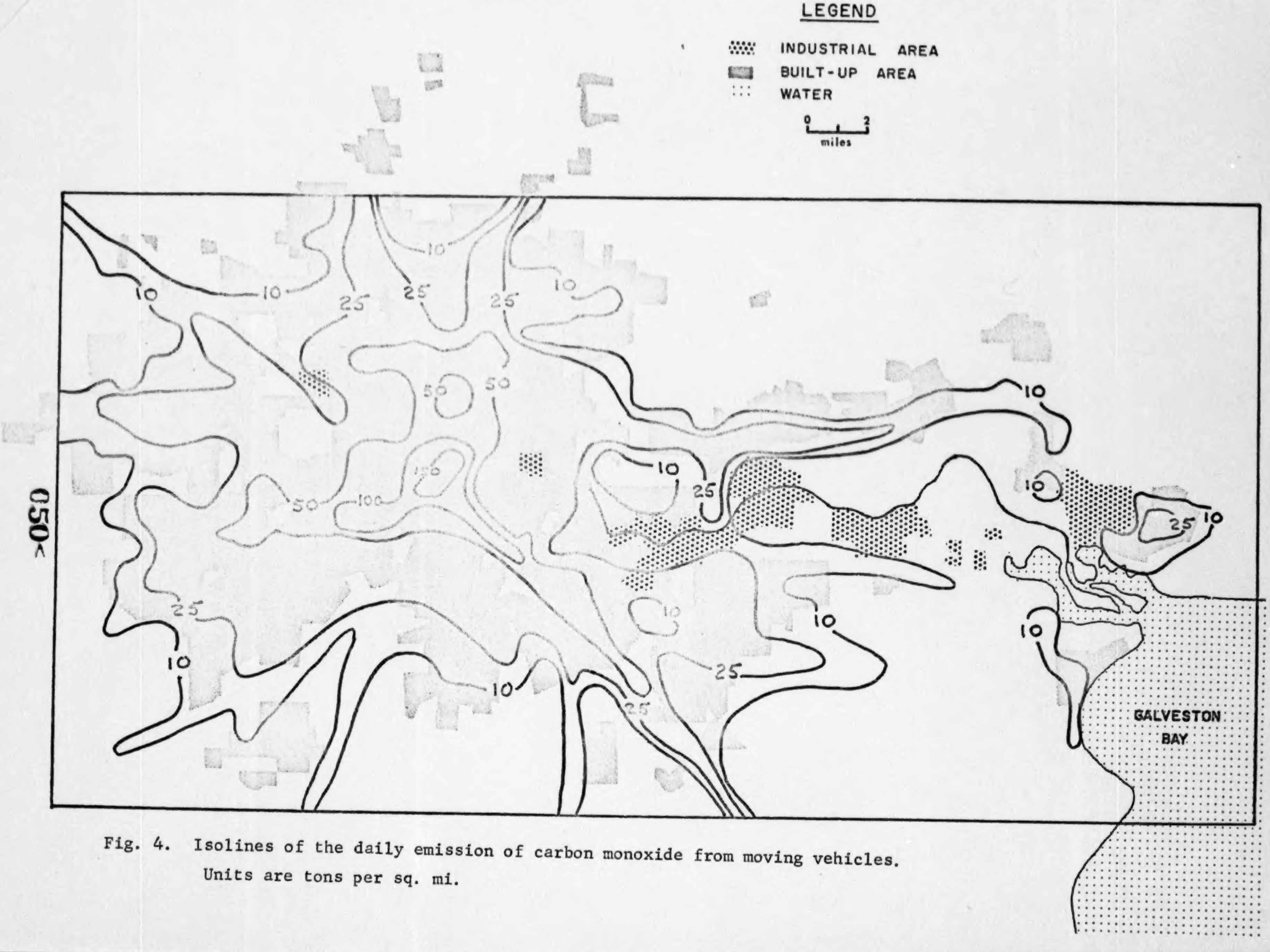
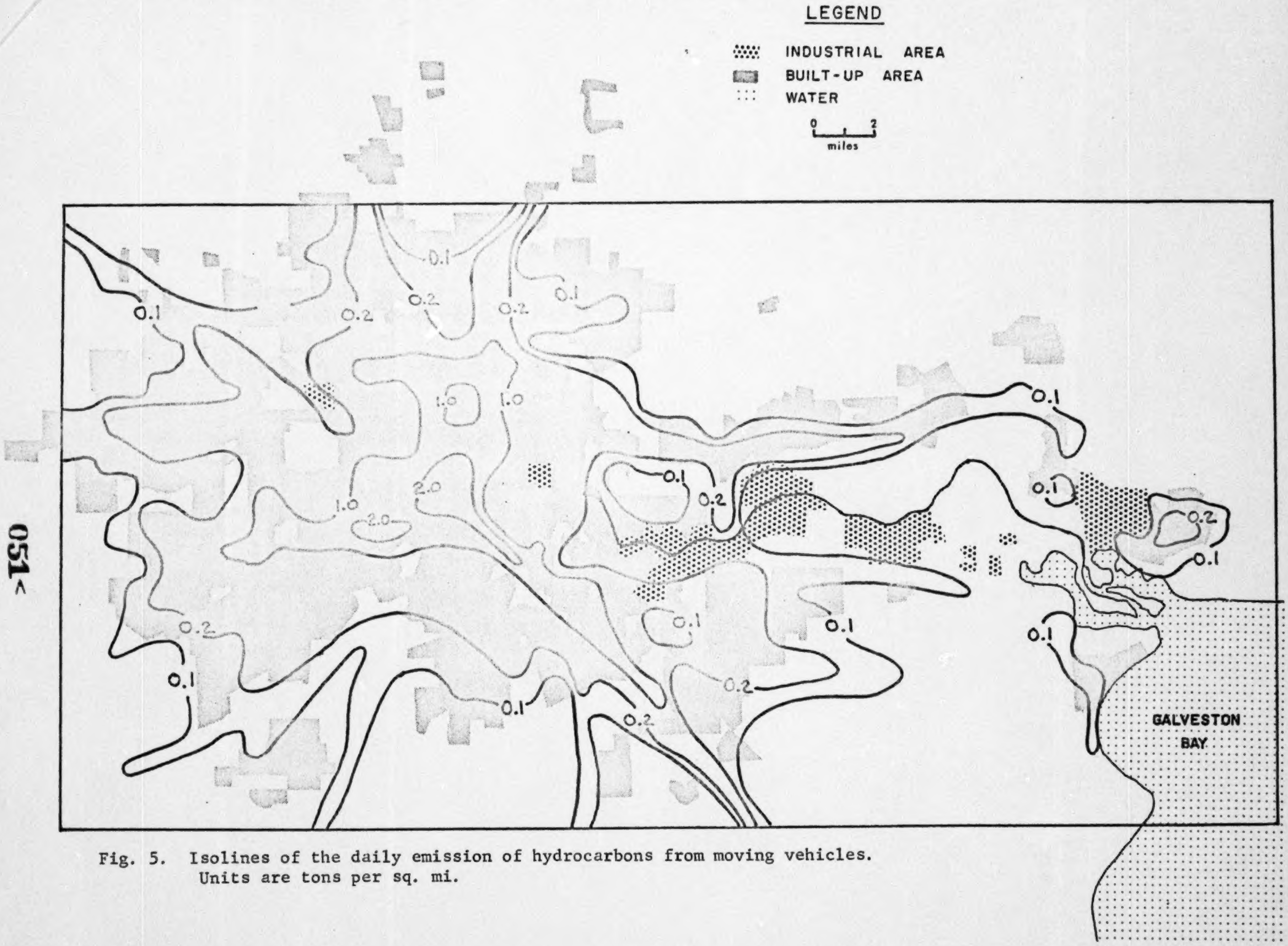

LEGEND
INDUSTRIAL AREA
BUILT-UP AREA
WATER
0 2
miles
GALVESTON BAY
10
25
50
100
150

Fig. 4. Isolines of the daily emission of carbon monoxide from moving vehicles. Units are tons per sq. mi.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INDUSTRIAL AREA
BUILT-UP AREA
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0.1
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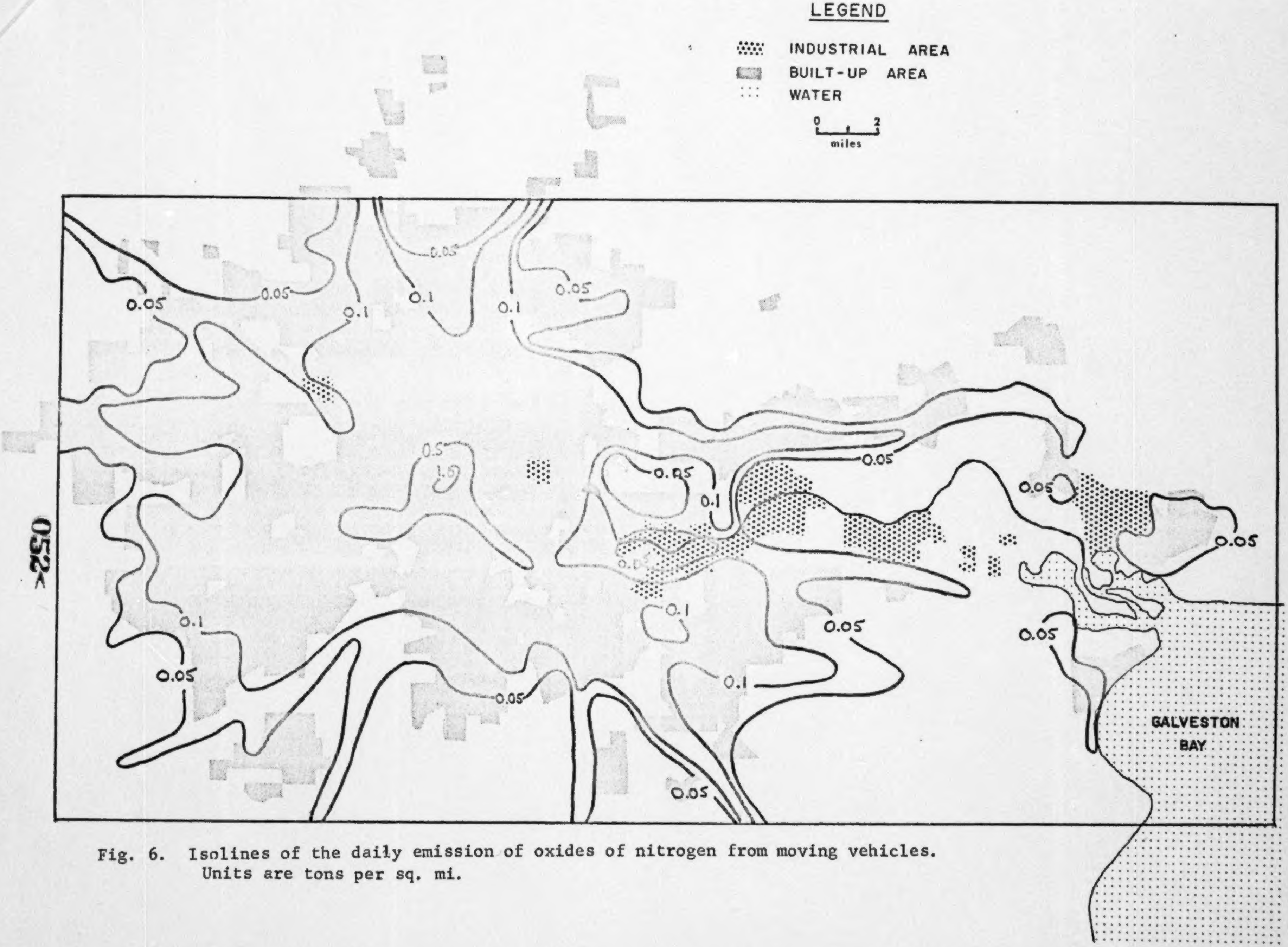
0.1
GALVESTON
BAY

Fig. 5. Isolines of the daily emission of hydrocarbons from moving vehicles. Units are tons per sq. mi.


LEGEND
INDUSTRIAL AREA
BUILT-UP AREA
WATER
0
2
miles
0.05
0.05
0.1
0.1
0.05
0.1
0.05
0.5
1.0
0.05
0.1
0.05
0.05
0.05
0.05
0.1
0.05
0.05
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0.05
0.1
0.05
GALVESTON BAY

Fig. 6. Isolines of the daily emission of oxides of nitrogen from moving vehicles. Units are tons per sq. mi.

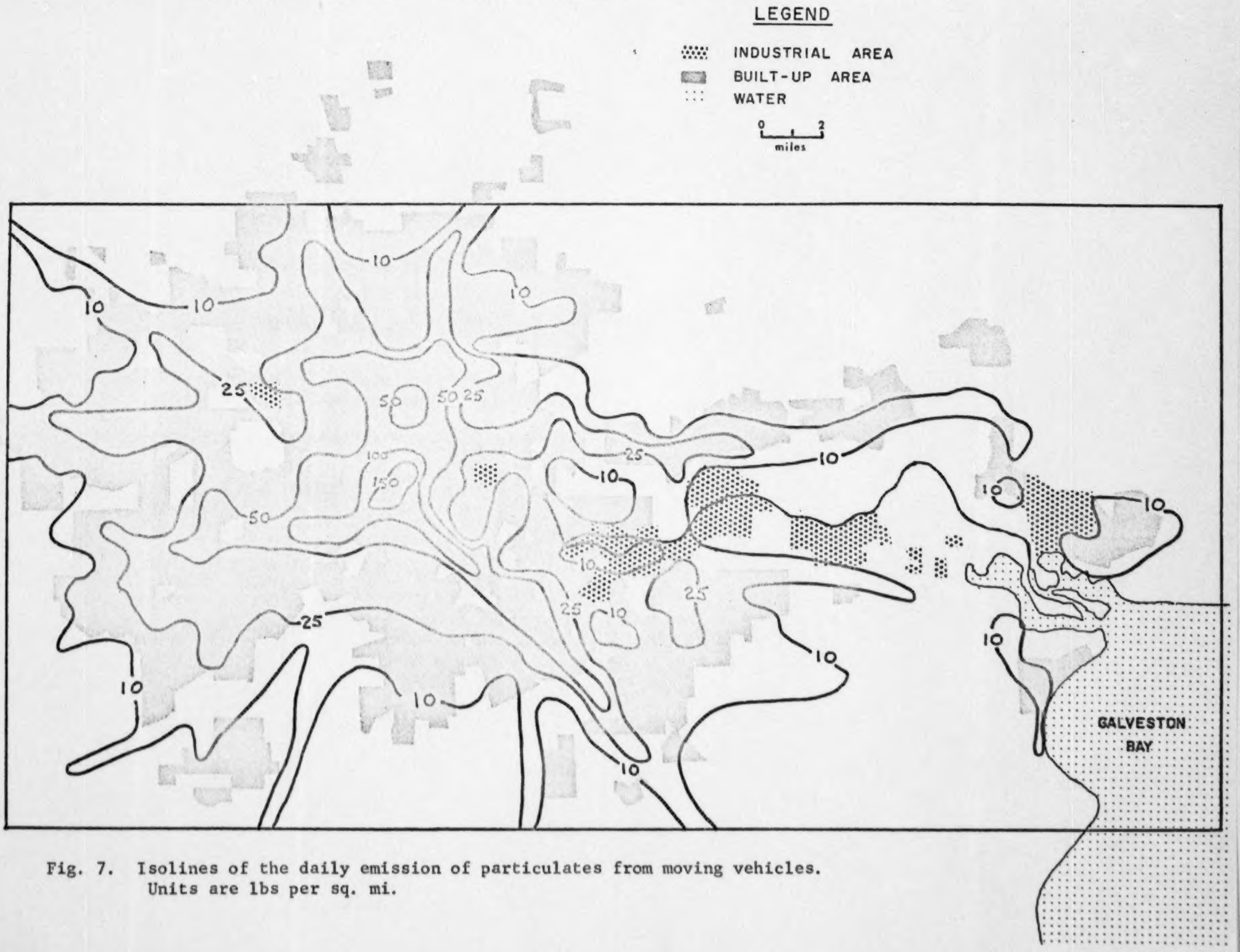
LEGEND
INDUSTRIAL AREA
BUILT-UP AREA
WATER
0 2
miles
GALVESTON BAY
10
25
50
100
150

Fig. 7. Isolines of the daily emission of particulates from moving vehicles. Units are lbs per sq. mi.

1975 Federal standards. Therefore, we believe that the magnitudes shown are reasonable ones.

The emission pattern of hydrocarbons includes the evaporative losses which occur during both moving and stationary periods. The above-mentioned figures for losses due to evaporation were used in this calculation and were applied uniformly over the built-up area.

Daily totals of emissions. The emissions from each zone and for each of the pollutants were summed to obtain the daily emissions for the study area. These results are shown in Table 2.

Table 2 Emissions from motor vehicles.

Pollutant	LB day^{-1}	Percent
Carbon monoxide	2.04×10^6	86.1
Hydrocarbons	1.66×10^5	7.0
Oxides of nitrogen	1.24×10^5	5.2
Particulates	1.92×10^4	0.8
Oxides of sulphur	1.05×10^4	0.4
Organic acids	6.34×10^3	0.3
Aldehydes	4.56×10^3	0.2
		100.0

Temporal variation of emissions. Figure 8 shows the variation of vehicular traffic on a major street during an average weekday. This hourly pattern is repeated in most portions of the study area. Slight temporal departures occur with increasing distance from the central business district, but they are less than the one-hour intervals used on the abscissa in Figure 8. Therefore, we assumed that the temporal variation shown in this figure could be multiplied by the area emissions in a particular zone to give the variation of the pollutant emissions with time from the zone of interest. If T(t) is the functional form of the temporal variation of vehicular traffic within a zone and F(x,y) is the functional form of the areal variation (e.g., the isolines shown in Figures 4,5,6 and 7) then the source function (E(x,y,t)) is

$$E(x,y,t) = F(x,y)\ T(t). \qquad (1)$$

A source function can be determined by various schemes of interpolation for each pollutant of interest. Likewise, source functions similar to Eq.(1) can be formulated for stationary sources (for a common pollutant) and may be used as the surface boundary condition when atmospheric diffusion is regarded as a boundary-value problem.

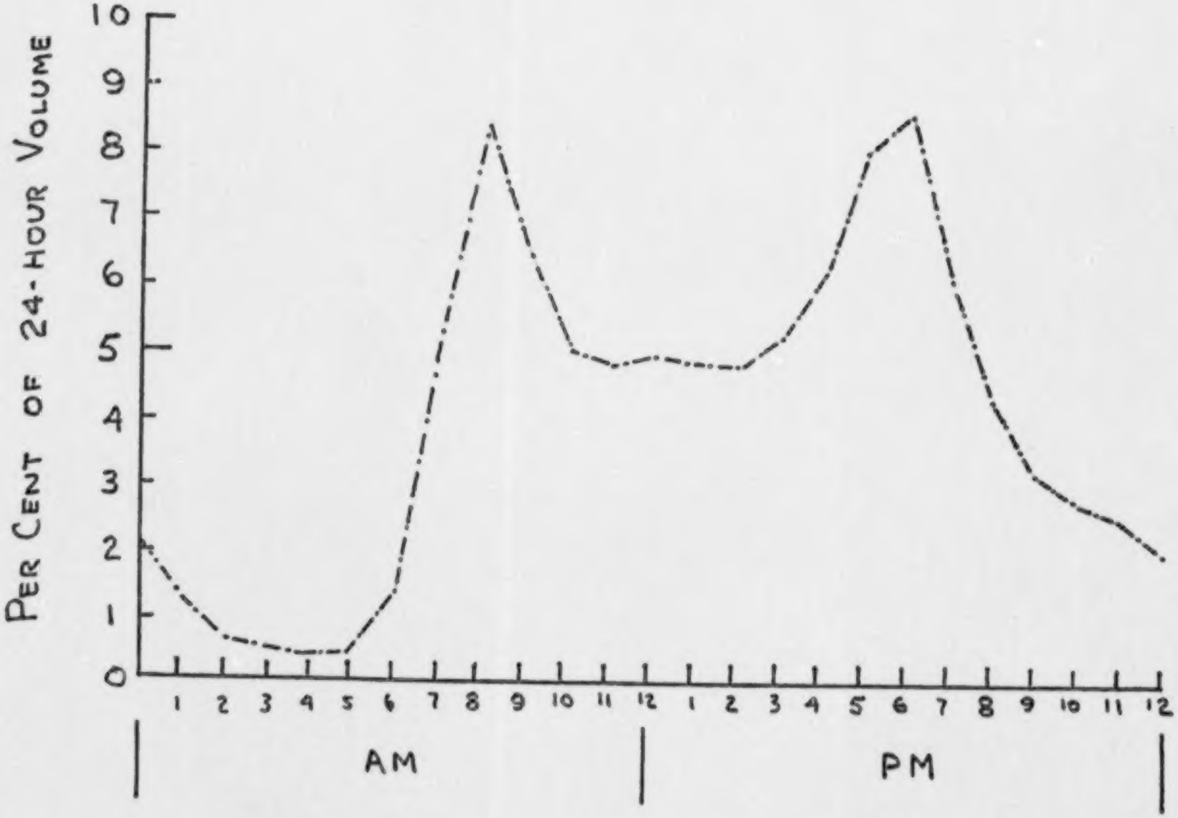

Fig. 8. Hourly variation of traffic.

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(3) DERIVATION OF A NUMERICAL MODEL FOR PREDICTING GASEOUS DIFFUSION IN THE ATMOSPHERE

A computerized numerical dispersion model for SO_2 was designed for Nashville, Tennessee. The model represents the complete transport equation numerically integrated for a period of 2 hours in three-dimensional space. Three-dimensional advection, diffusion, and variations in topography are included in the model. In addition, the numerical solution includes the effects of chemical decay, of source strength, and of a correction term for the truncation error. The diffusion portion of the model includes a variable, vertical exchange coefficient.

The basic assumption of the model is that the local change of SO_2 in the atmosphere obeys the following equation:

$$\frac{\partial \bar{Q}}{\partial t} = -\left[\bar{u}\frac{\partial \bar{Q}}{\partial x} + \bar{v}\frac{\partial \bar{Q}}{\partial y} + \bar{w}\frac{\partial \bar{Q}}{\partial z}\right] + \frac{\partial}{\partial x}\left[K(x)\frac{\partial \bar{Q}}{\partial x}\right] + \frac{\partial}{\partial y}\left[K(y)\frac{\partial \bar{Q}}{\partial y}\right] + \frac{\partial}{\partial z}\left[K(z)\frac{\partial \bar{Q}}{\partial z}\right] + \bar{S} - \bar{E}$$

where

$\bar{Q}$ = average concentration of SO_2 in micrograms per cubic meter ($\mu g/m^3$)

$\bar{u}$ = average component of the wind speed in the x-direction in cm/sec

$\bar{v}$ = average component of the wind speed in the y-direction in cm/sec

$\bar{w}$ = average component of the wind speed in the z-direction in cm/sec

$K(x)$, $K(y)$, $K(z)$ = the coefficients of the eddy diffusion of SO_2 in the x,y, and z directions, respectively, in cm^2/sec (also called exchange coefficients)

$\bar{S}$ = source term in $\mu g/m^3/sec$

$\bar{E}$ = chemical decay in $\mu g/m^3/sec$

Physically, the first three terms on the right-hand side of the above equation represent the horizontal and vertical transport of SO_2 by the wind. Since u is not a function of Q, these terms are linear. The next three terms are expressions for the transfer of SO_2 in the system due to turbulent mixing. If $K(x)$ and $K(y)$ are constants, the only non-linear term in this equation is the term representing vertical diffusion. The average amount of SO_2 released into the atmosphere in time Δt is accounted for by $\bar{S}$. The last term on the right-hand side of the equation represents the chemical decay of SO_2 during time Δt.

Numerical integration of this equation was conducted through an explicit, finite-differencing scheme in a fixed coordinate system. This gave values of Q at the next time, $t_o + \Delta t$ is the time step.

Seven different variations in the numerical model were tested. The predicted fields of SO_2 were aligned parallel to the air flow in all cases. This alignment should have occurred if the advective portion of the model was functioning correctly. One variation of the model, with no vertical motion, showed that topographically-induced vertical advection can change local concentrations of SO_2 by as much as 20 percent of the predicted value. Hence, in regions where local relief can cause large-scale vertical motion, the vertical advection must be considered as a basic part of the numerical scheme. Another variation of the model considered the effect of no advection. In this model it was shown that horizontal diffusion could be neglected when the distance between horizontal grid points is 1.0 mile. Vertical diffusion also was another noteworthy result. This particular portion of the model kept large, local concentrations of SO_2 from accumulating at grid points where SO_2 was input to the system. The model became numerically unstable and solutions could not be achieved without the vertical diffusion term. This term also permitted intense mixing of the gaseous SO_2 and spread this gas through the depth of the model. Another test of the model was concerned with the chemical decay term. It was found that in a 2-hour forecast the chemical decay could account for losses of SO_2 of 10 to 20 percent of the predicted concentrations. The final test was used in the correction for the truncation term. This model showed that the parameter utilized to balance the errors due to truncation could be neglected because these errors were relatively small. By including the correction term, however, the small-scale oscillations in the predicted concentrations were damped out. In order to improve the likelihood of numerical stability, the truncation correction term should be used.

The boundary conditions imposed upon the model influenced the magnitude of the predicted values of SO_2 concentrations. The top level of the model functioned as a "lid" to all upward movement of SO_2 if sources were permitted to exist on this uppermost boundary. Such a condition may be desirable if strong temperature inversions exist in the lower atmosphere. The predicted concentration, in this case, corresponded with the observed values. When the sources from the top boundary were removed, reasonable results were also obtained; the results being smaller than in the preceeding case. Both of these boundary conditions appear to be feasible, but represent different atmospheric processes. The first one may be representative of atmosphic conditions of low-level inversions, while the second boundary condition could be used for a deep, neutrally-stable, atmospheric situation. The predicted ground-level concentration of SO_2 was two or three times greater than the observed values when diffusion was permitted across the top boundary.

This study has demonstrated that numerical techniques of modeling can be used in the forecasting of the diffusion of atmospheric pollutants. The model offers a high degree of flexibility by taking into account the following factors;

a. different wind speeds and directions can be input or calculated for every grid point in the model,
b. wind velocity can be varied in time,
c. source strengths can be varied in time and space,
d. atmospheric stability can be varied in time and space,
e. the effects of topography can be incorporated in the model

easily, and

f. the horizontal and vertical dimensions can be varied to suit the particular situation, the only limitation being on the storage capabilities of the electronic computer.

Computer time required to make a 24-hour forecast was less than 15-minutes. The computer operational time could be shortened by optimizing the computer program so that a minimum number of iterations is performed. Even though the model does not include variations in the horizontal exchange coefficient a subroutine can be added to allow these two parameters to vary.

The principal difficulty in this study was in obtaining data which would allow a meaningful evaluation to be made of the predicted parameter. The data available in many cases have not been taken in a manner which makes them compatible with the requirements of the numerical model. In other words, there is a definite lack of measurements of the vertical distribution of atmospheric pollutants. Simultaneous measurements of meteorological and aerometric information are also needed. Of particular importance is that wind measurements be taken at the heights of the sources.

The data found which incorporated the majority of above conditions were for Nashville, Tennessee, during the period 1958-1959. These data were used to establish the three-dimensional distribution of SO_2 and to derive a steady-state condition for the air flow and for the internal emissions of SO_2. This numerical model could be used to forecast the dispersion of atmospheric pollutants, such as CO, in other cities with only slight modification in the program. The most important problem would be to obtain data that would provide for the verification of the model.

(4) A STATISTICAL STUDY OF SAMPLING TECHNIQUES

A survey of suspended particulates was performed by the Houston Department of Public Health during the period from December 27, 1967 through December 24, 1968. The first 40 days of the survey (called the temporary survey) consisted of 24-hr suspended particulate counts obtained from 28 sites located throughout the Houston area (Fig. 1). As a result of statistical analyses of these data the number of sites was reduced from 28 to 17 and these 17 sites were used to collect 24-hr suspended particulate counts for the 10 months remaining in the survey (called the permanent survey).

Since several sites were omitted as a result of the temporary survey without regard to synoptic situation, this study attempts to determine if their omission could be more significant during certain weather conditions. Therefore, an attempt is made to see if the prevailing wind direction dictates the need for more or fewer sampling sites to represent adequately the distribution of suspended particulates.

WIND DIRECTION EFFECT

Data from the survey were grouped according to prevailing wind direction and comparisons were made of the means (using the t-test) and variances (using the F-test) among the sites to determine if sites were significantly different (at the 95% level) from neighboring sites. Figure 2 gives results of comparisons of the means and variances of the site omitted with the means and variances of the neighboring (within about 2 miles) permanent sites. Based on small sampling theory, it appears that the means and variances (of suspended particulate counts) of sites H,I, and A are significantly different from those of their corresponding surrounding permanent sites.

Every site was compared with each of the remaining sites giving a total of 136 comparisons for the permanent survey data with the results given in Figs. 3-8. For each sample (wind direction), the percent of all possible combinations of means and variances that are significantly different were evaluated and are given in Table I. It may be concluded that the probability two sites show significantly different means and variances is much greater during southerly flow than during northerly or easterly flow.

Table II shows the distribution of wind direction for the temporary survey compared with the distribution according to climatology. The distribution during the temporary survey fits quite well with the 1st and 4th quarter distribution but does not fit with the 2nd and 3rd quarters or the annual distribution. During these two quarters, the prevailing wind is from the south, as is the case for the annual distribution. As shown above, southerly winds tend to produce more "individuality" than do northerly or easterly winds, hence, the probability that significant errors have been made by the omission of sites is much greater during those periods when southerly winds prevail.

RAINFALL EFFECT

Several periods were chosen in which ½ inch or more rainfall was measured on several consecutive data collection days. For each site, the ratio of the mean suspended particulate count during the rainy period to the mean count of the preceeding dry period was computed and expressed as a percentage. The average percentage was calculated for all sites in each of the series chosen and is given in Table 3 along with the mean rainfall. It appears that rainfall amounting to ½ inch per day for a 2-3 day period reduces the suspended particulate count to about 80% of its value during the preceeding dry period, and an amount of about 1 inch per day reduces the count to about 65%.

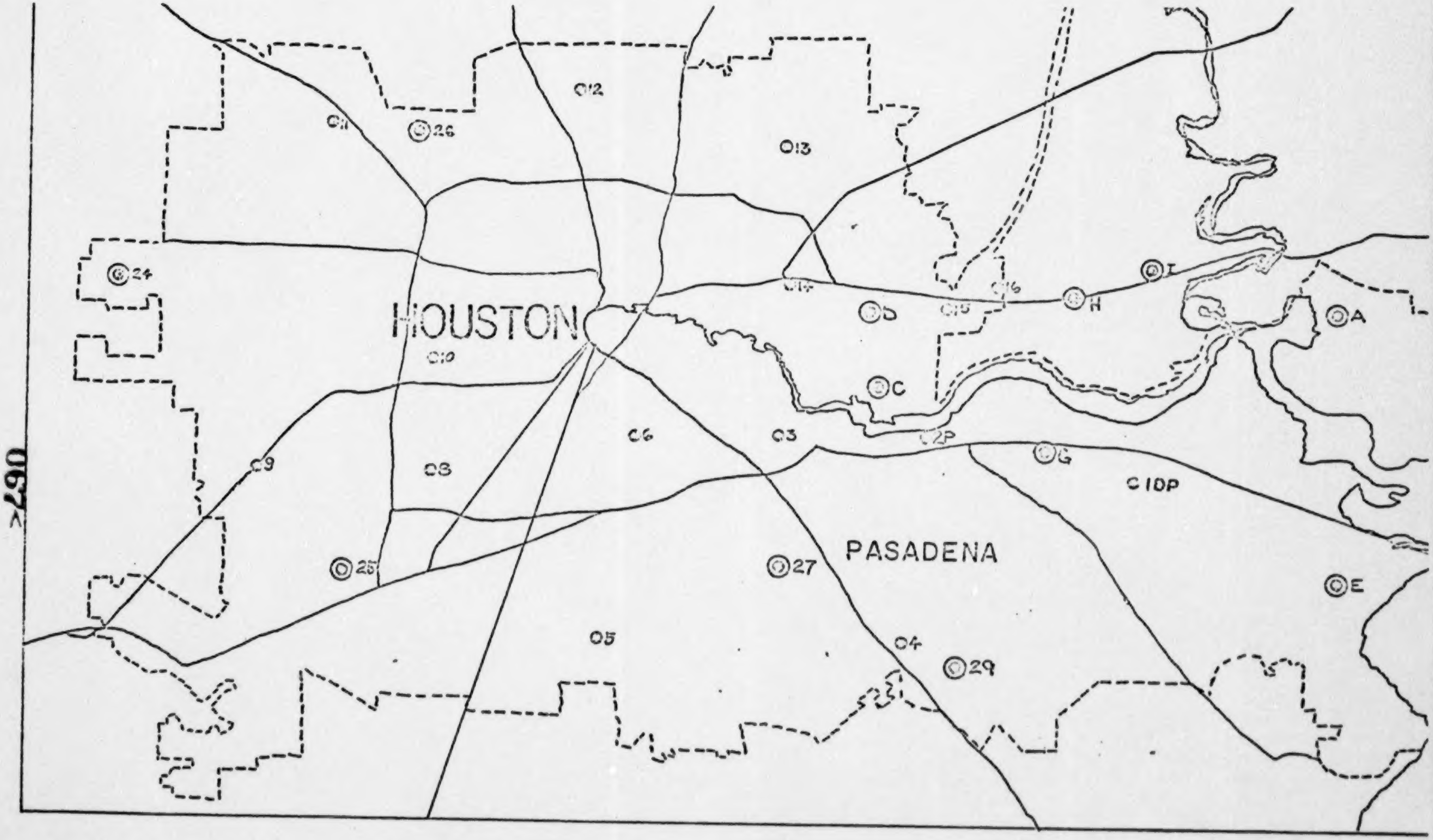
SUMMARY

1. Based on small sampling theory, data from three sites (H, I, and A) are significantly different from surrounding sites.

2. During periods of southerly winds more "individuality" is observed in the suspended particulate counts.

3. Results of the temporary survey may be applicable only during the winter months.

4. Suspended particulate counts are decreased by about 20% and 35% for rainfalls of ½ and 1 inch per day, respectively.



C11
26
C12
C13
24
HOUSTON
C10
C14
D
C15
C16
H
I
A
C
C2P
G
C10P
C3
C6
C8
C9
25
27
PASADENA
C5
C4
29
E

Figure 1. Suspended particulate sampling sites, the sites that are circled were omitted as the result of the temporary survey.

Table 1. Percent of comparisons that are significantly different.

Prevailing Wind	Means	Variances
North	18%	2%
East	27%	12%
South	74%	68%

Table 2. Mean Distribution of wind direction at Houston International Airport during the temporary survey and the mean quarterly and annual distribution during the period 1951-1960.

Wind Direction	Temporary Survey	1st	2nd	3rd	4th	Annual
South	35%	37%	58%	49%	30%	43%
North	37%	31%	16%	19%	35%	25%
East	28%	21%	17%	21%	24%	21%

Ⓐ	1DP
t	99
F	95

Ⓔ	1DP
t	80
F	<90

Ⓘ	1DP
t	99
F	99

Ⓗ	16	15
t	99	99
F	99	99

Ⓖ	1DP	2P
t	99	99
F	<95	<95

㉙	4
t	55
F	<95

Ⓓ	15	14	2P	3
t	95	70	80	95
F	<95	<95	<95	<95

Ⓒ	2P	15	3	14
t	99	95	95	70
F	<95	<95	<95	<95

㉗	4	3	5	6
t	60	99	55	80
F	<95	<95	<95	<95

㉖	11	12	10
t	70	80	99
F	<95	<95	95

㉔	11	9	10
t	55	70	0
F	95	<95	<95

㉕	9	8	5
t	70	80	55
F	<95	<95	<95

Figure 2. Probability that the means (t) and variances (F) are different for the sites omitted (circled) and the surrounding permanent sites; a site is considered significantly different when all surrounding sites have a value for both t and F of 95 or greater. (Example of notation: Ⓖ

Ⓖ	1DP	2P
t	99	99
F	<95	<95

, site G has been omitted and the neighboring permanent sites are site 1DP and site 2P. The nearest site, 1DP, has a mean that is different from that of site G and a variance that is not different. The next closest site, 2P, has a mean that is different and a variance that is not different from site G. Thus, stie G is not significantly different from both sites 1DP and 2P).

-Sites used for permanent survey-

t

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	1DP	2P
2		.30 19	.24 17	.30 18	.21 21	1.31 18	1.05 19	1.06 20	1.21 19	2.36 21	.61 19	1.06 13	1.14 19	.27 20	.34 20	.18 19	1.9 20
3	60		-.08 18	-.52 19	-.48 22	.75 19	.58 20	.56 21	.65 20	1.53 22	.21 20	.54 19	1.26 20	-.04 21	-.59 21	-.12 20	-1.9 21
4	55	<55		-.46 17	-.41 20	.90 17	.70 18	.69 19	.80 18	1.77 20	.31 18	.68 17	-1.20 18	.04 19	-.54 19	-.04 18	-1.92 19
5	60	70	60		.13 21	1.32 18	1.14 19	1.16 20	1.25 19	2.18 21	.78 19	1.12 13	-.75 19	.50 20	.05 20	.42 19	-1.35 20
6	55	60	60	55		1.42 21	1.20 22	1.22 23	1.35 22	2.42 24	.73 22	1.19 21	-1.01 22	.45 23	-.11 23	.36 21	-1.71 23
7	90	75	80	90	90		-.19 19	-.25 20	-.15 19	.79 21	-.62 19	-.25 18	-2.05 19	-.82 20	-1.65 20	-.90 19	-2.9 20
8	80	70	75	80	80	55		-.05 21	.05 20	.98 22	-.42 20	-.05 19	-1.90 70	-.64 21	-1.39 21	-.72 20	-2.7 21
9	80	70	75	80	80	60	<85		.10 21	1.09 23	-.40 22	0 20	-1.96 21	-.63 22	-1.41 22	-.71 21	-2.8 22
10	80	70	75	80	90	55	<85	<55		1.0 22	-.50 20	-.10 19	-2.03 20	-.72 21	-1.56 21	-.81 20	-2.92 21
11	97	90	95	97.5	97.5	75	90	80	80		-1.48 22	-1.16 24	-2.97 22	-1.63 23	-2.76 23	-1.73 22	-4.18 23
12	70	55	60	75	75	70	60	60	70	90		.38 19	-1.56 20	-.26 21	-.93 21	-.34 20	-2.37 21
13	80	70	75	80	80	60	<55	0	<55	80	60		-1.87 19	-.61 20	-1.40 20	-.69 19	-2.78 20
14	80	80	80	75	80	97.5	95	95	95	99	90	95		1.28 21	.95 21	1.18 20	-.42 21
15	60	<85	<55	65	60	80	75	70	75	90	60	70	80		-.56 22	-.08 21	-.96 22
16	60	70	70	<55	55	90	90	90	90	99	80	90	80	70		.47 21	-1.71 22
1DP	55	55	<85	60	60	80	75	75	75	95	60	75	80	<55	60		-1.55 21
2P	95	95	95	90	95	99.5	99	99	99.5	99.5	97.5	99	60	80	95	95	

Figure 3. Probability that means are different during north winds.

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-Sites used for permanent survey-

F

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	1DP	2P
2		2.6	1.7	2.5	1.7	1.4	1.7	1.5	1.3	1.0	1.6	1.3	3.3	2.4	1.2	2.3	2.0
3			1.5	1.0	1.5	1.9	1.5	1.7	2.0	2.5	1.6	20	1.3	1.4	2.2	1.1	1.3
4				1.5	1.0	1.2	1.0	1.1	1.3	1.6	1.0	1.3	2.0	1.4	1.4	1.4	1.2
5					1.5	1.8	1.4	1.6	2.0	2.4	1.5	1.9	1.3	1.0	2.1	1.1	1.3
6						1.2	1.0	1.1	1.3	1.6	1.0	1.3	2.0	1.4	1.4	1.4	1.2
7							1.3	1.1	1.1	1.3	1.2	1.1	2.4	1.8	1.2	1.7	1.4
8								1.1	1.4	1.7	1.0	1.3	1.9	1.4	1.4	1.4	1.2
9									1.2	1.5	1.1	1.2	2.2	1.6	1.3	1.5	1.3
10										1.2	1.3	1.0	2.6	1.9	1.4	1.8	1.6
11											1.6	1.3	3.2	2.3	1.4	2.2	1.9
12												1.3	2.6	1.5	1.4	1.4	1.2
13													2.6	1.9	1.1	1.8	1.5
14	95									95				1.4	2.8	1.4	1.7
15															2.1	1.0	1.2
16			ALL	REST	< 95								95			2.6	1.7
1DP																	1.2
2P																	

Figure 4. Probability that variances are different during north winds.

-Sites used for permanent survey-

t

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	1DP	2P
2		-1.13 12	2.87 14	.23 16	.36 12	2.23 14	1.40 14	2.17 14	1.66 14	2.31 14	1.64 14	1.87 14	-.46 14	.83 13	.07 13	-.45 12	-1.52 13
3	80		3.33 12	.50 14	1.12 10	2.81 12	1.98 12	2.75 12	2.42 12	2.39 12	2.20 12	2.42 12	.19 12	1.51 11	1.07 11	.55 10	-.34 11
4	99	99.5		-1.89 16	-1.75 12	-.55 14	-.69 14	-.52 14	-1.30 14	-.55 14	-.54 14	-.45 14	-1.85 14	-1.29 13	-2.50 13	-2.70 12	-3.66 13
5	60	70	95		.42 14	1.55 16	1.20 16	1.54 16	1.16 16	1.56 16	1.35 16	1.47 16	-.24 16	.76 15	.26 15	-.03 14	-.81 15
6	60	80	95	60		1.30 12	.82 12	1.28 12	.84 12	1.34 12	.99 12	1.14 12	-.57 12	.36 11	-.27 11	-.62 10	-1.44 11
7	97.5	99	70	90	90		-.28 14	0 14	-.70 14	0 14	-.12 14	0 14	-1.57 14	-.86 13	-1.93 13	-2.19 12	-3.16 13
8	90	95	75	80	75	60		.28 14	-.24 14	.29 14	.15 14	.26 14	-1.26 14	-.47 13	-1.22 13	-1.48 12	-2.35 13
9	95	99	70	90	90	0	60		-.68 14	0 14	-.12 14	0 14	-1.56 14	-.84 13	-1.89 13	-2.15 12	-3.11 13
10	95	97.5	90	80	80	75	60	75		.73 14	.43 14	.59 14	.59 14	-.36 13	-1.40 13	-1.75 12	-2.76 13
11	97.5	99	70	90	90	0	60	0	75		-.12 14	0 14	-1.58 14	-.88 12	-1.99 13	-2.26 12	-3.23 13
12	90	97.5	70	90	80	55	55	55	60	55		-.11 14	-1.39 14	-.63 13	-1.43 13	-1.68 12	-2.57 13
13	95	97.5	60	90	80	0	60	0	70	0	55		-1.49 14	-.76 13	-1.64 13	-1.88 12	-2.79 13
14	60	55	95	60	70	90	90	90	70	90	90	90		.88 13	.46 13	.16 12	-.44 13
15	75	90	90	75	60	80	60	80	60	80	70	75	80		-.70 12	-1.01 11	-1.85 12
16	<55	80	97.5	60	60	95	80	95	90	95	90	90	60	75		-.46 11	-1.43 12
1DP	60	70	99	<55	75	97.5	90	97.5	95	97.5	95	95	55	80	60		-.38 11
2P	90	60	99.5	80	90	99.5	97.5	99.5	99	99.5	99	99	60	95	90	80	

Figure 5. Probability that means are different during east winds.

-Sites used for permanent survey-

F X 10

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	1DP	2P
2		20	11	5.5	24	1.3	29	14	11	11	26	22	79	26	13	18	24
3			18	28	12	1.6	15	15	21	18	13	11	40	13	15	11	12
4				51	22	1.2	27	13	12	10	24	20	72	24	12	17	22
5	95		95		23	44	19	40	59	51	21	25	14	21	41	30	23
6						1.9	12	17	26	22	11	11	33	11	18	13	10
7				95			23	11	13	11	21	18	63	21	11	15	19
8								21	31	27	11	13	27	11	22	16	12
9				95					14	13	19	16	58	19	10	14	18
10				99						11	28	24	84	28	15	20	26
11				95							24	20	72	24	12	17	22
12												12	36	10	19	14	11
13													35	12	16	12	11
14	99		99			99			99	99	95	95		36	58	43	37
15															19	14	11
16				95									95			14	18
1PD													95				13
2P																	

Figure 6. Probability that variances are different during east winds.

-Sites used for permanent survey-

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	1DP	2P
									t								
2		-.28 128	6.90 131	.73 126	-.27 121	4.00 116	5.01 123	5.03 127	2.72 124	4.39 128	.31 126	.50 128	-6.21 124	-7.02 127	-7.02 125	2.62 128	-.92 125
3	60		6.45 127	.93 122	0 117	3.37 112	4.80 119	4.81 123	2.75 120	4.24 124	.57 123	.75 124	-5.58 120	-6.41 123	-6.20 121	2.21 124	-.56 121
4	99	99		-5.84 125	-6.57 120	-2.26 115	-1.17 122	-1.83 126	-3.13 123	-2.93 127	-7.25 125	-7.85 127	-11.97 123	-11.92 126	-14.96 124	-5.22 127	-8.68 124
5	75	80	99		-.93 115	3.16 110	4.10 117	4.07 121	1.95 118	3.43 122	-.46 120	-.33 122	-6.55 118	-7.25 121	-7.47 119	1.27 122	-7.64 119
6	60	0	99	80		3.59 105	4.82 112	4.85 116	2.72 113	4.28 117	.57 115	.75 117	-5.44 113	-6.20 116	-6.12 114	2.21 117	-.56 114
7	99	99	97.5	99	99		.89 107	.58 111	-1.03 108	-.20 112	-3.99 110	-4.17 112	-8.87 108	-9.12 111	-10.7 109	-2.28 112	-5.18 109
8	99	99	80	99	99	80		-.40 118	-1.85 115	-1.23 119	-5.04 117	-5.30 119	-9.97 115	-10.2 118	-13. 116	-3.29 119	-6.27 116
9	99	99	95	99	99	70	60		-1.66 119	-.9 123	-5.08 121	-5.37 123	-10.28 119	-10.9 122	-12.5 120	-3.18 123	-6.41 120
10	99	99	99	98	99	80	95	90		1.01 120	-2.54 128	-2.55 120	-7.95 116	-8.48 119	-9.16 117	-.93 120	-3.65 117
11	99	99	99	99	99	55	80	80	80		-4.39 122	-4.61 124	-9.39 120	-10.1 123	-12.0 121	-2.42 124	-5.76 121
12	60	70	99	60	70	99	99	99	99	99		.18 122	-6.5 118	-7.19 121	-7.54 119	1.91 122	-1.30 110
13	70	75	99	60	75	99	99	99	99	99	55		-6.92 120	-7.57 123	-8.16 121	1.88 124	-1.57 121
14	99	99	99	99	99	99	99	99	99	99	99	99		-1.21 119	.32 117	8.03 120	5.48 117
15	99	99	99	99	99	99	99	99	99	99	99	99	80		1.63 120	8.55 123	6.28 120
16	99	99	99	99	99	99	99	99	99	99	99	99	60	90		9.47 121	6.28 118
1DP	97.5	97.5	99	80	97.5	97.5	99	99	80	99	97.5	95	99	99	99		-3.22 121
2P	80	70	99	90	70	99	99	99	99	99	99	90	99	99	99	99	

Figure 7. Probability that means are different during south winds.

-Sites used for permanent survey-

F

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	1DP	2P
2		1.32	4.66	1.02	1.23	1.69	1.75	2.36	1.07	2.47	1.39	1.79	2.28	3.16	1.27	1.56	1.24
3			6.15	1.29	1.07	2.22	2.31	3.11	1.23	3.26	1.77	2.35	1.72	2.46	1.04	2.06	1.64
4	99	99		4.77	5.75	2.77	2.67	1.98	5.00	1.89	3.49	2.62	10.62	14.7	5.91	2.98	3.76
5			99		1.21	1.72	1.79	2.41	1.05	2.52	1.37	1.82	2.23	3.09	1.24	1.60	1.27
6			99			2.08	2.15	2.91	1.15	3.05	1.65	2.19	1.85	2.56	1.03	1.93	1.53
7	95	99	99	95	99		1.04	1.40	1.81	1.46	1.26	1.05	3.84	5.33	2.14	1.08	1.36
8	95	99	99	95	99			1.35	1.87	1.41	1.31	1.01	3.97	5.52	2.22	1.12	1.41
9	99	99	99	99	99				2.53	1.05	1.76	1.33	5.37	7.45	2.99	1.51	1.90
10			99			99	99	99		2.65	1.43	1.91	2.12	2.95	1.18	1.68	1.33
11	99	99	99	99	99				99		1.85	1.39	5.62	7.81	3.13	1.58	1.99
12		95	99		95			95		99		1.32	3.05	4.23	1.70	1.17	1.08
13	95	99	99	99	99								4.05	5.62	2.26	1.14	1.43
14	99	95	99	99	99	99	99	99		99	99	99		1.39	1.86	3.60	2.82
15	99	99	99	99	99	99	99	99		99	99	99			2.49	4.95	3.92
16			99			99	99	99		99	95	99	99	99		1.98	1.57
1DP	95	99	99	95	99	ALL REST <95		95		95			99	99	99		1.26
2P		95	99		95			99		99			99	99	95		

Figure 8. Probability that variances are different during south winds.

(5) MEASUREMENT OF SELECTED POLLUTANTS

(a) CARBON MONOXIDE

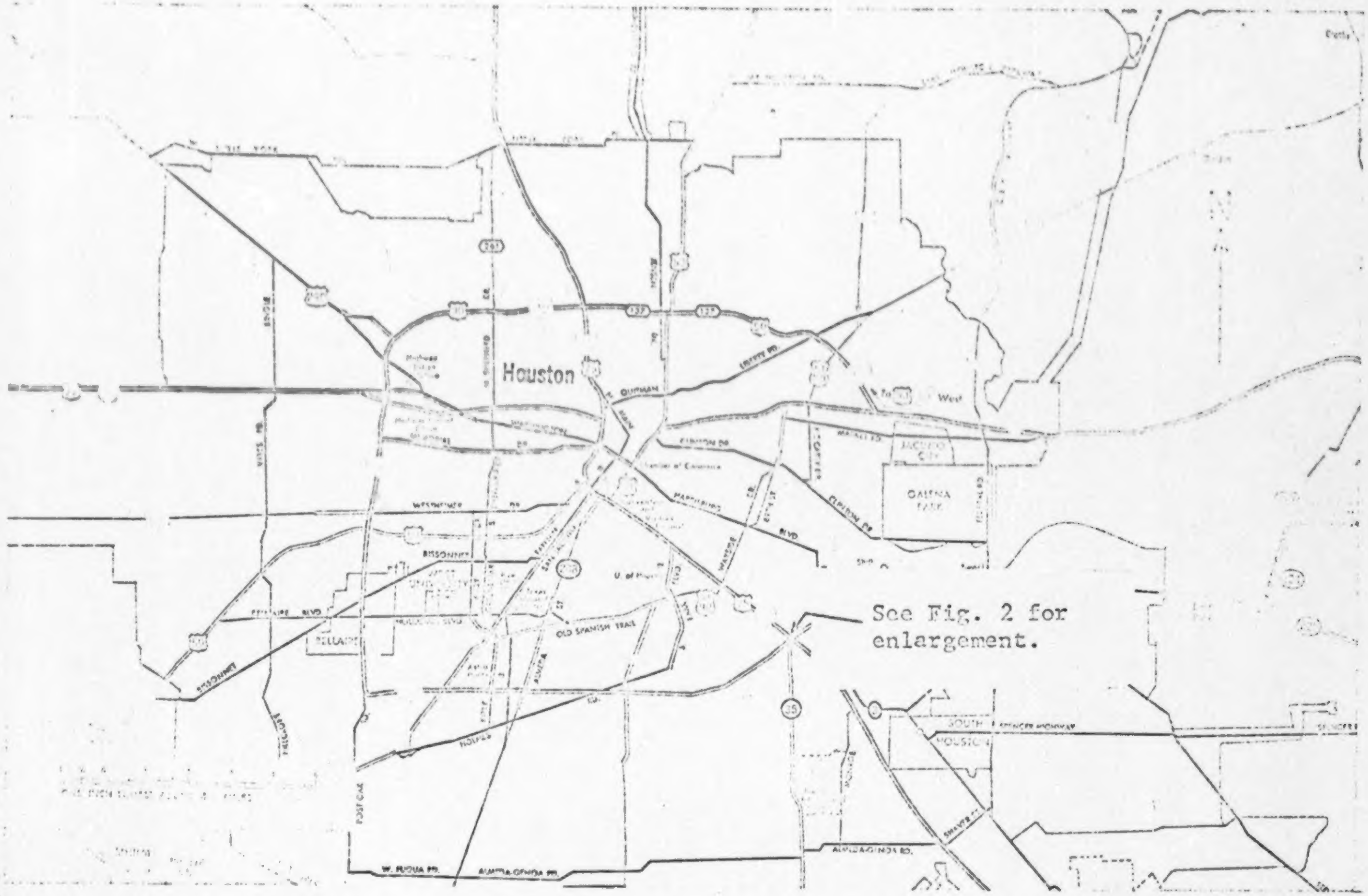
1969 Experiments

This section is concerned with carbon monoxide diffusion near a freeway interchange in Houston, Texas, during July 17-21, 1969. (Fig. 1&2) The experiment consisted of using three vertical samplers located 15 ft from the freeway and placed 6, 15 &30 ft above the ground. A fourth sampler was located near the ground at the freeway curb. Carbon monoxide observations were made during the daylight hours for all four samplers. The curbside sampler was operated during the night to obtain continuous carbon monoxide variations. Statistical correlations were made between carbon monoxide and certain meteorological parameters and between carbon monoxide and traffic. Vertical profiles of carbon monoxide were analyzed to show the variation of carbon monoxide from the ground level to 30 ft. Also, the variation of the vertical exchange coefficient was studied under different meteorological conditions.

Carbon monoxide measurements were taken, with a Beckman 315A Infra-red Analyzer, at four positions, of which three were in a vertical line.. The lowest sampler, or filter, was located 6 ft above the ground and was designated as Sampler 1. The second filter was located 15 ft above the ground and was designated as Sampler 2. The highest filter was placed 30 ft above the ground and was designated as Sampler

3. A fourth sampler was placed 6 ft above the ground in the middle of the working area, but this sampler was discontinued on the afternoon of July 18 due to the low concentrations being obtained there. Sampler 5 then was set up 12 ft from the curb and 1 ft above the ground.

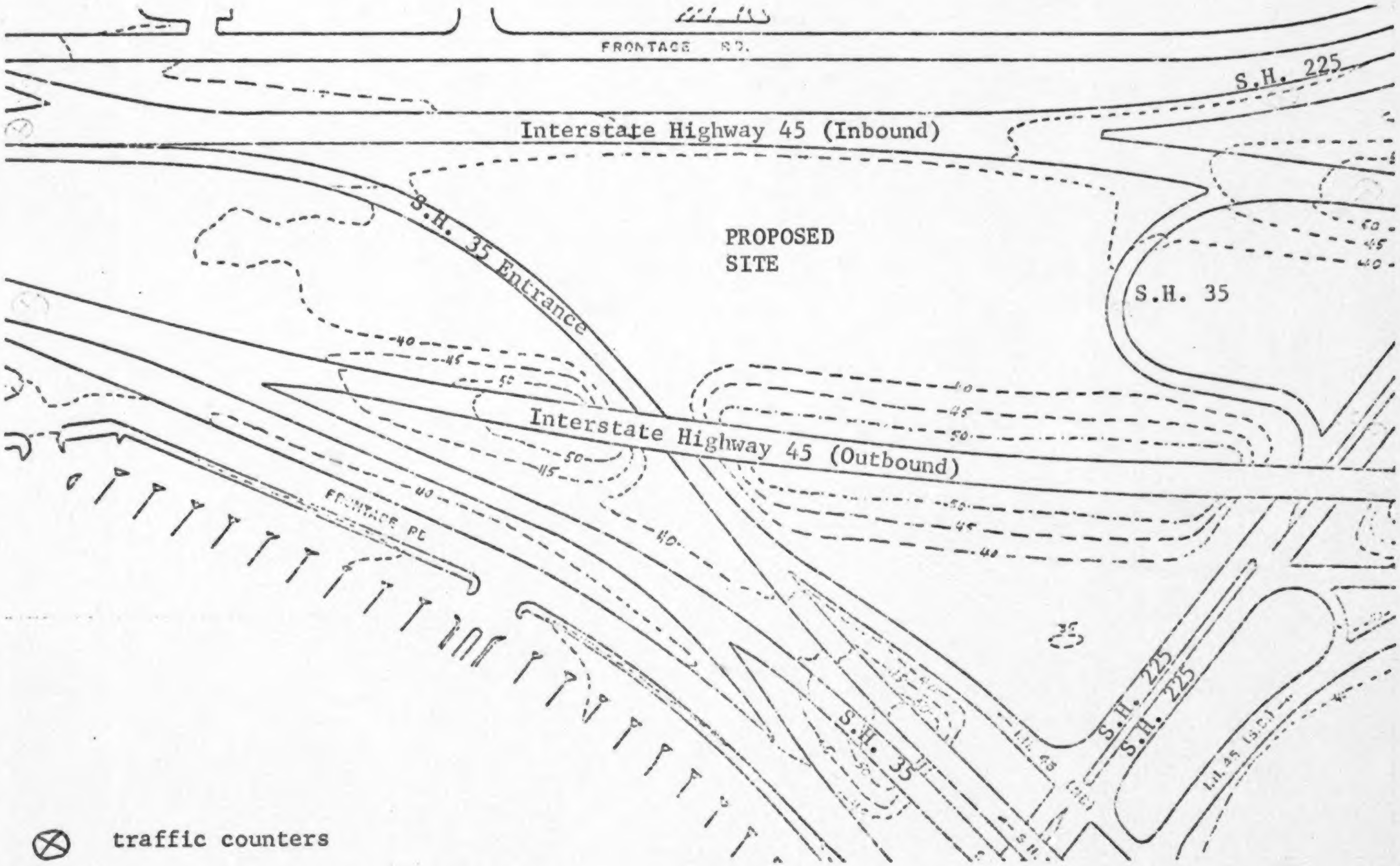
Figure 3 shows the variation of carbon monoxide throughout the days of the experiment. Figure 4 shows variations in the amount of traffic on the expressway. The plotted carbon monoxide concentrations were 15-min average values of each filter.


Houston
Quitman
Liberty Rd.
Clinton Dr.
Westheimer
Bissonnet
Bellaire
Bellaire Blvd
Old Spanish Trail
Harrisburg
Wayside Dr.
Galena Park
Jacinto City
South Houston
Spencer Highway
Almeda-Genoa Rd.
W. Fuqua Rd.
Post Oak
West
35

See Fig. 2 for enlargement.

Fig. 1. Location of site.

Reproduced from best available copy.


FRONTAGE RD.
S.H. 225
Interstate Highway 45 (Inbound)
PROPOSED SITE
S.H. 35
S.H. 35 Entrance
40
45
50
Interstate Highway 45 (Outbound)
FRONTAGE PL
35
S.H. 225
S.H. 225
S.H. 35
I.H. 45
I.H. 45 (S.B.)

⊗ traffic counters

-40-- contour lines (Ft)

1 in. = 100 ft

Fig. 2. Location of site and traffic counters.

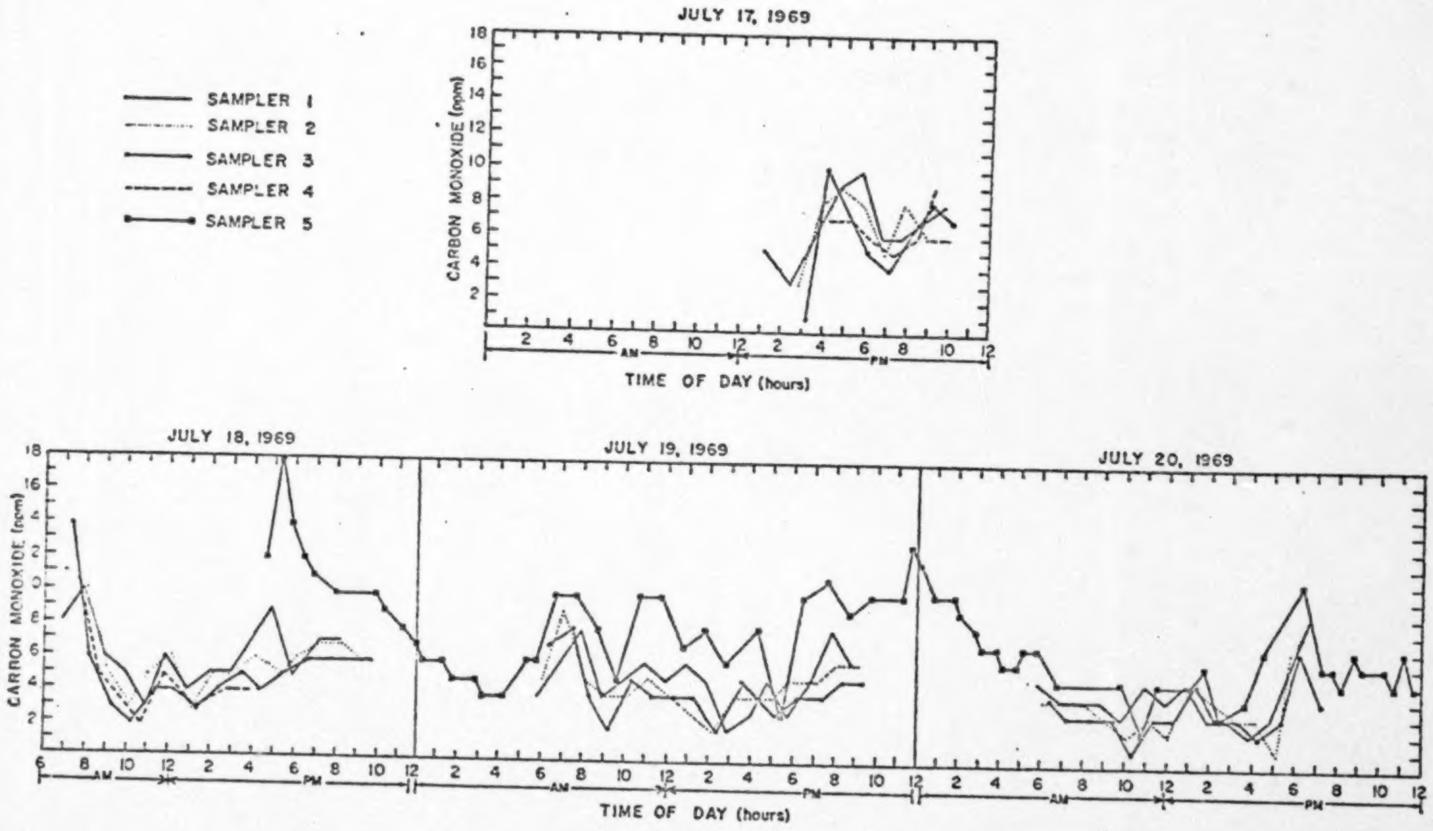


Fig. 3 - Carbon monoxide concentrations during the experimental period.

C81<

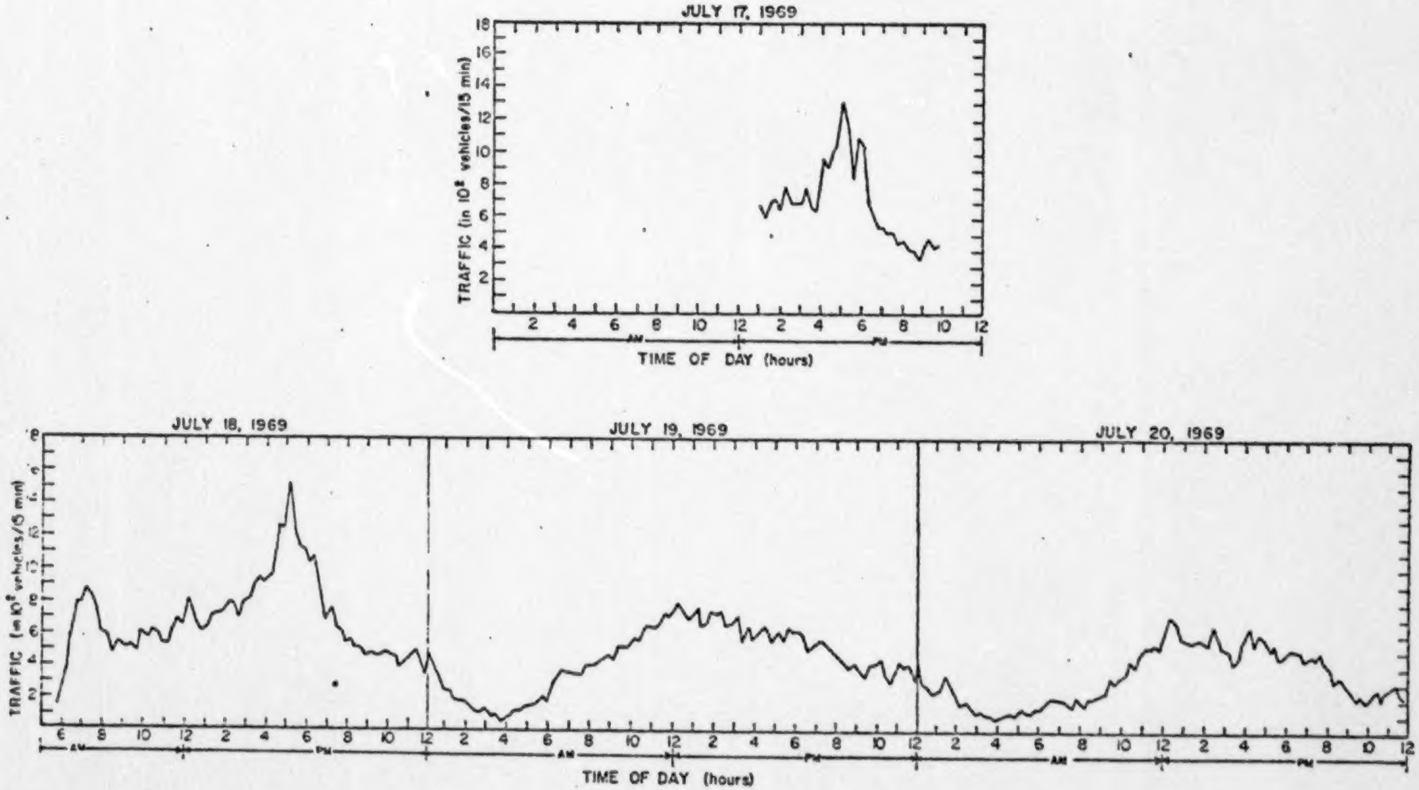


Fig. 4 - Traffic Density During The Experimental Period

Table I gives linear correlation coefficients for carbon monoxide concentrations and traffic amounts. Correlations varied erratically from one sampler to another. One reason for the large variation could be wind eddies that brought additional carbon monoxide from surrounding freeways, and the afternoon rains that occurred at the time of the experiment.

Table I. Correlation coefficients for carbon monoxide and traffic.

Sampler	1	2	3	4	5
July 17	+0.44	+0.73[a]	+0.29	+0.03	
July 18	+0.36	-0.03	+0.11	+0.03	+0.89[a]
July 19	-0.47	-0.64[a]	-0.55[a]		+0.46[a]
July 20	-0.06	-0.05	-0.07		-0.17
Average	+0.07	+0.02	-0.07		+0.52

[a] Values are mathematically significant at the 5% level.

Table II shows correlation coefficients for carbon monoxide and wind speed. These values are negative, as would be expected.

Table II. Correlation coefficients for carbon monoxide and wind speed.

Sampler	1	2	3	5
July 18	-0.48	-0.42	-0.38	
July 19	-0.58[a]	-0.32	-0.06	-0.13
July 20	-0.40	-0.42	-0.51	-0.50
Average	-0.49	-0.41	-0.31	-0.38

[a] Value is mathematically significant at the 5% level.

Wind direction was correlated with carbon monoxide concentrations using a 16-point wind scale. Results are presented in Table III

It is interesting to note that the correlation coefficients changed from all positive, except one, on July 18 to all negative on July 20. This variation could have been due to the change from weekday traffic to weekend traffic. Average values show close to zero correlation for the three days.

Table III.[a] Correlation coefficients for carbon monoxide and wind direction.

Sampler	1	2	3	4	5
July 18	-0.23	+0.02	+0.09	+0.16	+0.44
July 19	+0.43	-0.06	+0.16		+0.36
July 20	-0.04	-0.24	-0.35		-0.36
Average	+0.19	-0.10	-0.04		+0.16

[a] None of the values in this table were mathematically significant at the 5% level.

Vertical profiles of carbon monoxide were derived for every 30 min on days that the experiment was carried out. Sampling locations were changed every 15 min, so each sampler had a 15-min carbon monoxide concentration value during each hour of the day. These 15-min values were then connected for each sampler.

Carbon monoxide concentrations for Samplers 1, 2, and 3 were read from the charts every 30 min in order to obtain the vertical profiles.

In all graphs a tolerance of ±1 ppm (sensitivity of the instrument) was used to figure the type of carbon monoxide profiles. If the profile was within X ± 1 ppm it was considered as "iso-CO", that is, unchanged with height. Profiles were designated as upper maximum, lower maximum, center maximum, or center minimum. Table IV gives the percentages for each type of profile for each day of the experiment, as well as the total percentages.

Table IV. Percentage of occurrence of specified carbon monoxide profiles.

	Total	Thursday	Friday	Saturday	Sunday
Iso-CO	78.3%	75%	73.1%	75.9%	88%
Upper Max	2.2%	0%	3.8%	3.4%	0%
Lower Max	13.0%	16.7%	19.2%	10.3%	8%
Center Min	4.3%	0%	0%	10.3%	4%
Center Max	2.2%	8.3%	3.8%	0%	0%

To evaluate the vertical exchange coefficient, use was made of Sutton's solution to the diffusion equation for neutral equilibrium over a smooth or short grass surface (Sutton, 1953). The equation was given by:

$$\psi(x, z) = \frac{\zeta}{a^{b}\Gamma(c)K(z)^{c}u^{-d}x^{c}} \exp\left[\frac{-\bar{u}z^{a}}{a^{2}K(z)x}\right]$$

where $a = \frac{9}{7}$, $b = \frac{16}{9}$, $c = \frac{8}{9}$, $d = \frac{1}{9}$, ζ is the strength of the source measured in gm sec^{-1} cm^{-1}, and $\Gamma(x)$, the Gamma function. The above equation presents the concentration at some distance x from the source and some height z above the surface. $\bar{u}$ is the mean wind, which is blowing at right angles to the y-axis.

The variation of K(z) needed to produce the carbon monoxide concentrations determined by means of the above equation were analysed. On the four consecutive days of the experiment the vertical exchange coefficient increased during the morning until late afternoon when a decrease was observed

1970 Experiments

The 1970 freeway experiment work was conducted from July 29 through August 1. This period was selected in order to obtain, as nearly as possible, meteorologically similar days to those on which a similar experiment was performed a year before.

The site chosen for the 1970 experiment was the same as that used in 1969. This location was the interchange of the Gulf Freeway and State Highway 225 in Houston, Texas.

A traffic counter was placed across the freeway at the location of the carbon monoxide samplers and traffic counts were made available in 15-min totals from the Texas Highway Department.

The carbon monoxide measurements were taken with a Beckman 315A infra-red analyzer. This was the same unit as used in the 1969 experiment.

In this experiment, the carbon monoxide measurements were taken at four positions, with three of these being in the vertical. The samplers, or filters, were positioned along an overhead sign support. The lowest, sampler 4, was located 1 ft above the ground and 3 ft from the curb. A second sampler, designated sampler 3 was located directly above sampler 4 at a height of 12 ft. Sampler 2 was positioned directly over samplers 3 and 4 at 25 ft. A fourth filter, sampler 1, was positioned on the sign itself, directly over the center lane of traffic, at a height of 25 ft. This was in order to check the rate of vertical diffusion.

The measurements of carbon monoxide were taken every 15 minutes using a four-way valve system. This sampling procedure began each morning at 6:30 AM and continued until 8:00 PM. At this time smapler 4 was operated continuously throughout the night to give a lengthy uninterrupted sample and to study the diurnal variation of carbon monoxide.

Two anemometers were placed at the sampling sites, one was 3 ft above the ground and the other was 25 ft above the ground.

A Robitzsch radiation recorder gave a continuous strip chart measurement of solar radiation, Temperature and humidity measurements were taken by a recording hygrothermograph. To insure the realiability of the information from the instrument, sling psychrometer measurements were taken every hour.

Variations in the data were compared to those obtained in the 1969 experiment. Correlation coefficients relating carbon monoxide to : 1) traffic density, 2) wind speed, and 3) wind direction, were obtained.

Correlation coefficients were worked out for each sampler and each day. These coefficients were obtained by a linear regression of carbon monoxide concentrations on traffic density, wind speed, and wind direction.

Table V shows the results of the correlation of carbon monoxide concentration with traffic. The correlation coefficients were averaged daily using Fishers' z' transformation (Brooks and Carruthers), since the individual correlation coefficients are biased as to the sample. Table VI shows the 95% confidence limits for the daily averages of the correlation coefficients. These limits define the range of values of the correlation coefficients 95% of the time.

The values for samplers 2,3, and 4 show that a fraction of the variance is caused by the correlation of carbon monoxide with traffic density. This fractional correlation shows that the amount of carbon monoxide received by the samplers was dependent on factors other than that of traffic density. On the other hand, sampler 1 showed a marked correlation of amount of carbon monoxide and traffic density. At this sampler the correlation of traffic and carbon monoxide explains more than 50% of variance in the data. This is due primarily to the location of the sampler, 25 ft above the center lane of traffic.

Tables VII and VIII show the daily correlation coefficients, averages and 95% confidence levels obtained by the regression of carbon monoxide on wind speed. The results of these tables show that as wind speed increases the amount of carbon monoxide reaching the samplers decreased. This is due to the increased rates of mixing and diffusion of the carbon monoxide with the ambient air. The inverse is also true, the lower the wind speed the higher the carbon monoxide concentration.

Tables IX and X show the dependence of carbon monoxide concentration reaching the sampler on wind direction. As the winds become more perpendicular to the samplers the time which the carbon monoxide has to diffuse approaches a minimum.

Vertical profiles of carbon monoxide were obtained from samplers 2, 3, and 4 for each 30 minute time span on the days that the experiment was conducted. The sampling interval was 15 minutes so that each of the samplers had a 15 min carbon monoxide concentration value for each hour of the day. These 15 minute values were then connected, and the carbon monoxide concentrations were then taken off the diagrams every 30 minutes in order to obtain the vertical profiles.

The values showed that there was a marked decrease of carbon monoxide with height. This can be explained by the location of the samplers, since sampler 4 was only a foot off the ground, at exhaust level. This would give rise, as expected, to the predominance of the lower maximum values as shown in Table VII. The tolerance used on the graphs was ± 1 ppm. If the change in carbon monoxide concentration was within x ± 1 ppm from the bottom to the top of the layer it was considered to be Iso-CO, unchanged with height.

A temperature profile was obtained by the use of two temperature sensors located on the sign standard at elevations of 1 and 18 ft. The difference in readings between these two sensors was never greater than 1°C (within the sensitivity of the instrument) so it can be assumed that the temperature of the layer was constant. From this it can be assumed that the atmospheric stability, which is dependent on the temperature lapse rate did not play an extensive role and that the vertical pictures represent the actual conditions of vertical concentrations of carbon monoxide.

Table V CO vs Traffic

Date	Sampler 1	2	3	4	Avg
29 July	-0.42	-0.17	+0.15	+0.90	+0.25
30 July	-0.07	-0.23	-0.22	+0.72	+0.10
31 July	-0.12	-0.03	+0.01	+0.70	+0.20

Table VI CO vs Traffic 95% confidence limits (days)

	Upper	Lower
29 July	+0.50	-0.04
30 July	+0.40	-0.11
31 July	+0.40	+0.00

Table VII CO vs Wind Speed

Date	Sampler 1	2	3	4	Avg
29 July	-0.21	+0.31	0.00	+0.45	+0.14
30 July	-0.53	-0.53	-0.09	-0.39	-0.39
31 July	-0.52	-0.31	-0.35	-0.06	-0.31

Table VIII CO vs Wind Speed 95% confidence limits (days)

	Upper	Lower
29 July	0.49	-0.24
30 July	-0.24	-0.61
31 July	-0.05	-0.55

Table IX CO vs Wind Direction

Sampler	1	2	3	4	Avg
Date					
29 July	0.00	0.00	0.00	0.00	0.00
30 July	+0.04	-0.05	+0.01	+0.19	+0.05
31 July	-0.40	-0.06	-0.01	-0.07	-0.14

Table X CO vs Wind Direction 95% confidence limits (days)

	Upper	Lower
29 July	+0.37	-0.37
30 July	+0.32	-0.24
31 July	+0.16	-0.42

Table XI Percent Occurrence of Vertical Profiles

	July 29	July 30	July 31	
Iso-CO	0%	4.54%	0%	1.69%
L Max	100%	72.72%	100%	89.83%
U Max	0%	0%	0%	0%
C Max	0%	0%	0%	0%
C Min	0%	22.72%	0%	8.47%

DOWNTOWN EXPERIMENT

A statistical analysis of the downtown data was determined in the same manner as in the freeway experiment. Tables XII and XIII show correlation coefficients for carbon monoxide and wind speed and carbon monoxide and wind direction, respectively. Very little can be inferred from these correlation coefficients since the positive correlation explains at most 10% of the variance. Table XII does show, however, that there is a small positive correlation between carbon monoxide and wind speed in the downtown region.

Table XIV represents correlation coefficients for carbon monoxide and relative humidity. The effect of stratification is apparent from the positive sign attributed to the lowest sampler, but the correlation is weak. Correlation coefficients for carbon monoxide and Main Street traffic are shown in Table XV.

Correlation coefficients were obtained by using the downtown meteorological data of Houston, Texas. Data were obtained approximately five city blocks from the location of the experiment at the Weather Bureau.

Carbon monoxide values found in the downtown region are influenced by tall buildings. These buildings cause the carbon monoxide and other pollutants to be channeled down the streets. These buildings also affect wind speed and direction. A thorough study of carbon monoxide in a downtown region would necessitate the building of a downtown model to study the effects of wind movement over a city.

The results obtained show that there is a positive correlation between carbon monoxide and traffic. A negative correlation exists between carbon monoxide and wind speed, while an almost zero correlation is found between carbon monoxide and wind direction. Carbon monoxide concentrations found in the downtown area show marked differences, in some areas, from those found near the freeway, presumably because of changes that are produced in meteorological conditions as a result of the city.

Table XIV.* Correlation coefficients for carbon monoxide and relative humidity.

Sampler Levels	Correlation Coefficients
Lower	+ 0.16
Middle	- 0.03
Upper	- 0.09
Average	+ 0.02

* None of the values in this table were mathematically significant at the 5% level.

Table XV. Correlation coefficients for carbon monoxide and traffic.

Sampler Levels	Correlation Coefficients
Lower	+ 0.43*
Middle	+ 0.53*
Upper	+ 0.51*
Average	+ 0.49

* Values were mathematically significant at the 5% level.

Table XII.* Correlation coefficients for carbon monoxide and wind speed.

Sampler Levels	Correlation Coefficients
Lower	+ 0.08
Middle	+ 0.30
Upper	+ 0.24
Average	+ 0.21

* None of the values in this table were mathematically significant at the 5% level.

Table XIII.* Correlation coefficients for carbon monoxide and wind direction.

Sampler Levels	Correlation Coefficients
Lower	+ 0.07
Middle	0.0
Upper	- 0.01
Average	+ 0.02

* None of the values in this table were mathematically significant at the 5% level.

Two downtown experiments were made during the fall of 1970. The first experiment was from October 8 through October 11 and the second was from November 27 through November 30. These two experiments were designed to study the monthly variation of carbon monoxide in a downtown region. The experiments were located at the corner of Capitol and Main in downtown Houston. Carbon monoxide samplers were placed on a 30 ft light pole at the above mentioned intersection. Sampler 1 was positioned on the top of the pole and sampler 2 was placed 15 ft above the ground on the pole. An anemometer and wind vane was situated on the top of the light pole along with a vertical anemometer. Another wind system, similar to the above, was placed 6 ft from the building on the Main Street side. Use was also made of a Barnes infra-red sensor to determine IR values on the pavement, surrounding building, and clouds. Temperature sensors were also placed vertically along the building to obtain a temperature differential. These data were also supplimented with meteorological data obtained from Hobby airport, Ellington AFB, Houston Intercontinental airport, and the downtown Houston Weather Bureau.

IR measurements varied from 16 to 32C, with the majority of the measurements falling between 22 and 26C. The measurements were taken of Capitol and Main Streets and of several buildings surrounding the site. Sky radiation ranged from -10 to 14C with cloud radiation around 16 to 18C.

Vertical wind speed was analysed to show a correlation between the updrafts and carbon monoxide concentration. Little could be inferred, however, due to the rapid fluctuations between updrafts and downdrafts. In addition to the vertical anemometer located on Capitol, one was placed on the Main Street side of the building at a distance of 8 ft, horizontally, from the building. The vertical anemometer on Capitol gave an average reading of zero during most of the day. An increase to +1 or +2 mph (up) was noted during the early evening. The vertical component on the Main Street side was around -3 or -4 mph during the daylight hours. A drop to -1 or -2 mph was noted during the late evening and night. It was felt that the high values occuring on the Main Street side were from the thermal currents around the buildings. More work should be done in this area so as to understand better the total wind flow patterns that are associated with city buildings.

Carbon monoxide values varied from 2 to 10 ppm with the higher values being associated with heavier traffic flows. Average carbon monoxide concentrations were around 3-6 ppm, which were found during most of the days. Variations during the late evening and early morning hours ranged from 1 to 2 ppm.

Another important aspect of the downtown experiments was to gain further understanding of the wind flow around the buildings in downtown Houston. Wind velocity causes a great many pollutants to be transported by advection. It is anticipated that carbon monoxide concentration can be forecast, given certian basic ~~pa~~rameters, such as wind velocity, source emission, etc. In order to do this, however, one must first understand the atmospheric capability for transporting pollutants. One of these transport properties is advection and it is felt that a better understanding of the wind flow field in a downtown region is essential for maximum forecast potential.

During the waning months of this project a numerical model has been devised whereby the authors can study the wind flow patterns around buildings. It is anticipated that four or five buildings may be used in the model for verification purposes and that an accurate forecast model for carbon monoxide can be obtained.

(5) (b) THE DISTRIBUTION ON Mn AND Br IN AN URBAN AREA AS REVEALED THROUGH ACTIVATION ANALYSIS

1. INTRODUCTION

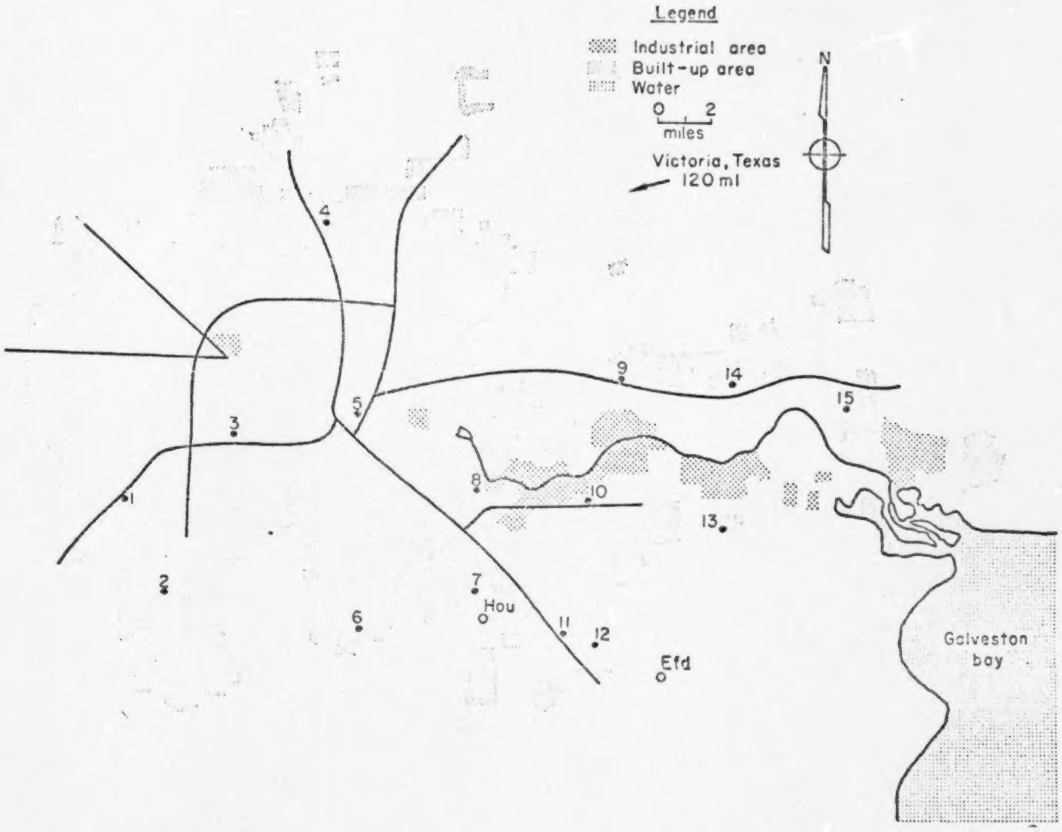
ONE OF the first problems encountered in the study of air pollution in a metropolitan area is the identification of the various chemical constituents of pollution present in the atmosphere. This problem becomes almost intractable when a myriad of different industrial sources are located in an urban community. For example, in Houston, Texas, the major industries consist of oil refineries and petrochemical plants as well as secondary manufacturers such as steel mills, fertilizer companies, and paper mills. These industries are situated along the Houston Ship Channel which is located east of downtown Houston. The petrochemical plants produce more than 300 organic and inorganic products and approximately 30 per cent of this country's total oil refining capacity is located in the Houston–Galveston industrial complex. Consequently, identification of the numerous constituents released into the atmosphere becomes very difficult, and requires the use of sophisticated analytical equipment. The analytical technique utilized here, in an attempt to identify some of the components of air pollution in Houston, was neutron activation of contaminated filter paper taken from high-volume air samplers. The locations of these 15 sampling stations are shown in FIG. 1.

2. DATA AND ANALYTICAL TECHNIQUE

The filter paper samples used in this study were provided by the city of Houston Public Health Department while the neutron activation was conducted by the Activation Analysis Research Laboratory of the Texas A&M Engineering Experiment Station. Only radionuclides with half-lives greater than 1 hr were considered. Some elements, such as lead, were not considered because of the complexity of the analytical procedure.

Meteorological data were available from the weather station located at Houston International Airport (Hou), which is situated approximately 7 miles SSW of the ship channel (FIG. 1). Supplementary weather data were available from Ellington Air Force Base (Efd) and a chemical company located near the ship channel. In general, the wind data from these latter two sites were compatible with those of the International Airport and are not presented in order to conserve space.

During the period 0900 CST on 28 December 1967 until about 0900 CST on 29 December 1967, the high-volume samplers were run continuously. On the average each sampler drew approximately 2235 m^3 of air through the filter paper in 24 hr. The active surface area of each filter paper was 406.5 cm^2. A total of 15 samples was acquired, one filter paper from each sampler. Precautions were taken to prevent contamination of the filter paper samples. Due to small variations in the sampling time and in the rate of air intake, all the data were normalized to units of μg per unit time per unit volume.


Legend
Industrial area
Built-up area
Water
0 2
miles
Victoria, Texas
120 mi
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1
2
3
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9
10
11
12
13
14
15
Hou
Efd
Galveston bay

FIG. 1. A map of Houston, Texas, and vicinity, illustrating the positions of major freeways as well as the locations of high-volume samplers utilized to collect the data for this study. Houston International Airport is indicated by Hou and Ellington AFB by Efd.

Fiberglass filters were used which had a collection efficiency of about 98 per cent for particles as small as 0.05μ. A small portion of each filter paper sample was irradiated in a thermal-neutron flux of 4.3×10^{12} neutrons cm^{-2} sec^{-1} for 1 hr. While the radioactive samples decayed, their activities were measured with a high resolution, 30 cm^3 Ge(Li) γ-ray detector coupled to a 3200-channel analyzer.

Due to extremely good sensitivity, there was little error introduced by other activity. Also a clean piece of irradiated filter paper was used as a standard to determine what peaks would be produced by clean filter paper. According to WEST (1968), neutron activation is sensitive and reliable to the picogram (pg) range. More information on activation analysis technology is given by GREEN (1968).

3. SYNOPTIC SITUATION

On 26 December 1967 a cold front passed Houston, bringing cool, dry continental polar air into the area. Following the passage of this frontal system, gusty, northerly winds were experienced in Houston until about 0500 CST, 28 December. After this time the wind speed gradually subsided to generally less than 7 kt by 1300 CST, 28 December, and became variable during the period 1800–2200 CST. Between 2300 CST, 28 December and 0900 CST, 29 December, the wind shifted to a variable NE to ENE flow. The wind rose presented in FIG. 2 portrays the air flow regime that existed during the period 0900 CST, 28 December, through 0900 CST, 29 December. In this figure notice that the winds from 050° occurred 25 per cent of the time while winds from 030° through 070° existed for about 62 per cent of the time.

TABLE 1 shows how the wind speeds were distributed during the period 0900 CST, 28 December to 0900 CST, 29 December 1967. In TABLE 1 notice that the predominant,

TABLE 1. OCCURRENCE OF VARIOUS WIND SPEEDS OBSERVED AT HOUSTON INTERNATIONAL AIRPORT DURING THE PERIOD 0900 CST, 28 DECEMBER THROUGH 0900 CST, 29 DECEMBER 1967

	Range of wind speed (kt)				
	3	3–7	8–12	13–17	>17
Occurrence (%)	0	79	13	8	0

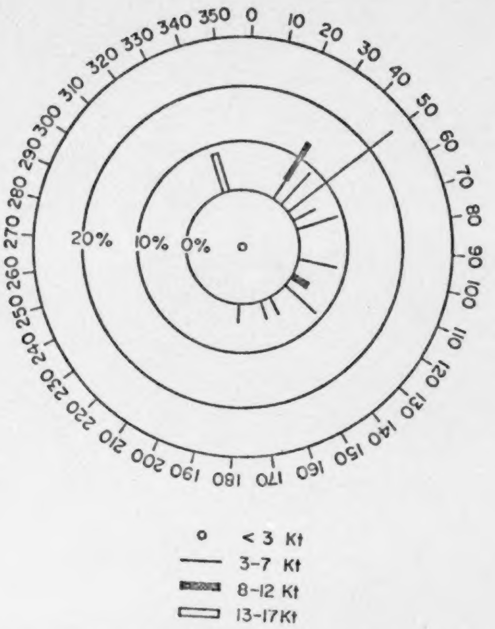

FIG. 2. Wind rose for Houston, Texas, during the period 0900 CST, 28 December 1967 to 0900 CST, 29 December 1967.

average wind speed was less than 8 kt. Wind speeds stronger than 7 kt generally occurred early in the sampling period; however, after 1200 CST, 28 December, all observed wind speeds were less than about 8 kt except for a 10 kt wind which was observed at 1700 CST.

In general, the data indicated that light winds from 040° to 070° existed continuously from 2300 CST, 28 December through 0900 CST, 29 December. During this 10-hr period no wind speed was observed to exceed 7 kt and the presence of a cool, dry air mass permitted nocturnal cooling to establish a thermally stable layer of air near the ground. FIGURE 3 shows the 0600 CST sounding from Victoria, Texas, which is located approximately 120 miles southwest of Houston. This figure reveals a strong

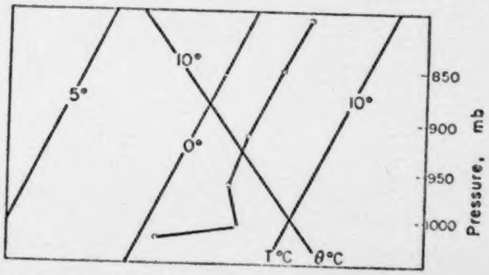

FIG. 3. Sounding for Victoria, Texas, 0600 CST, 29 December 1967.

nocturnal inversion about 300 to 400 ft in depth over Victoria with a stable layer of air extending to above the 850-mb level. Since both Houston and Victoria were in the same air mass, this sounding should be representative of the thermal structure of the atmosphere in the vicinity of Houston. Thereby it is believed that most of the effluvia released during the morning of 29 December were trapped below the 400 ft level. Under the prevailing wind conditions, this pollution was transported southwestward over the southern portion of Houston. Based on the recent work by ZUMWALT (1969), it can be concluded with confidence that this proposed movement is reasonable since the winds-aloft reports from surrounding stations indicated that, over Houston, the wind at the 1000-ft level was probably from about 070° to 080° at 7–8 kt during the period 2300 CST, 28 December, through 0900 CST, 29 December. Also, surface winds at Houston International Airport and Ellington AFB ranged from 050° to 060° at about 3–5 kt during the same time period.

4. RESULTS OF ACTIVATION ANALYSIS

Analysis of the activities of the irradiated filter paper samples revealed two photopeaks for ^{82}Br; however, only the 0·55 MeV peak was intense enough to analyze quantitatively without significant error. One other intense peak occurred, namely ^{56}Mn at 0.84 MeV. Large quantities of these two radionuclides were detected at every sampling site except for those stations located north (upwind) of the ship channel. The analysis for the distribution of Mn is presented in FIG. 4 while the analysis for Br is shown in FIG. 5.

In FIG. 4 notice that the range of measured concentrations of Mn is from 0.02 to 0.46 μg m^{-3} with the region of maximum values located over the southern half of Houston. Also notice that upwind concentrations are relatively small compared with the values over the southern portion of the city. Since FIG. 2 suggests that the predominant wind direction was from 030° to 050°, the implication given by FIG. 4 is that the Mn compounds should have originated northeast of the region of large concentrations. This premise is proposed because there are no known sources of Mn over the southern regions of the city. However, along the ship channel, there are several cement companies, chemical plants, and a steel mill, all being possible sources of various compounds of Mn which could be released into the atmosphere as process losses. Since the coastline of the Gulf of Mexico is located only about 50 miles from Houston, particulate material released through the "breaking" of waves would be a likely source of many chemical constituents. However, only one episode of light, variable SE winds did occur during the period 1800–2100 CST on 28 December. The wind speed during this time period averaged only about 6 kt so that little particulate material could have originated in the Gulf of Mexico; especially, since the upper-level air flow was from the NW through NE for a period of at least 48 hr.

The arithmetic mean values of the concentration of Mn for three other cities are presented in TABLE 2. These data were obtained from the National Air Sampling Network (NASN). Notice that most of the Mn concentrations measured in Houston during one, 24 hr period are an order of magnitude larger than the mean values presented for Boston and Chicago.

From all the data available from the NASN, analyses of suspended particulates measured by high-volume samplers also revealed that the maximum concentration

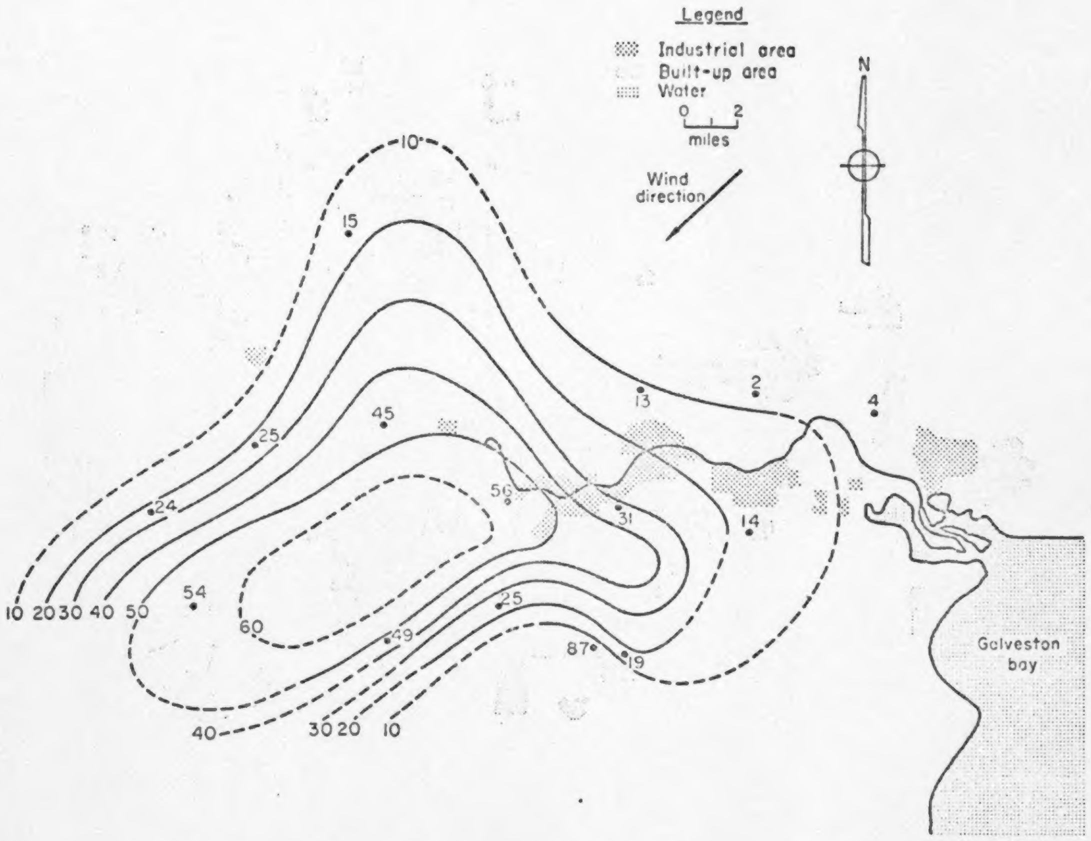
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FIG. 4. Normalized concentrations of Mn × 10^{-2} $\mu g\ m^{-3}$ during a 24 hr period on 28–29 December 1967. Dashed contours indicate regions of uncertainty in the analysis.

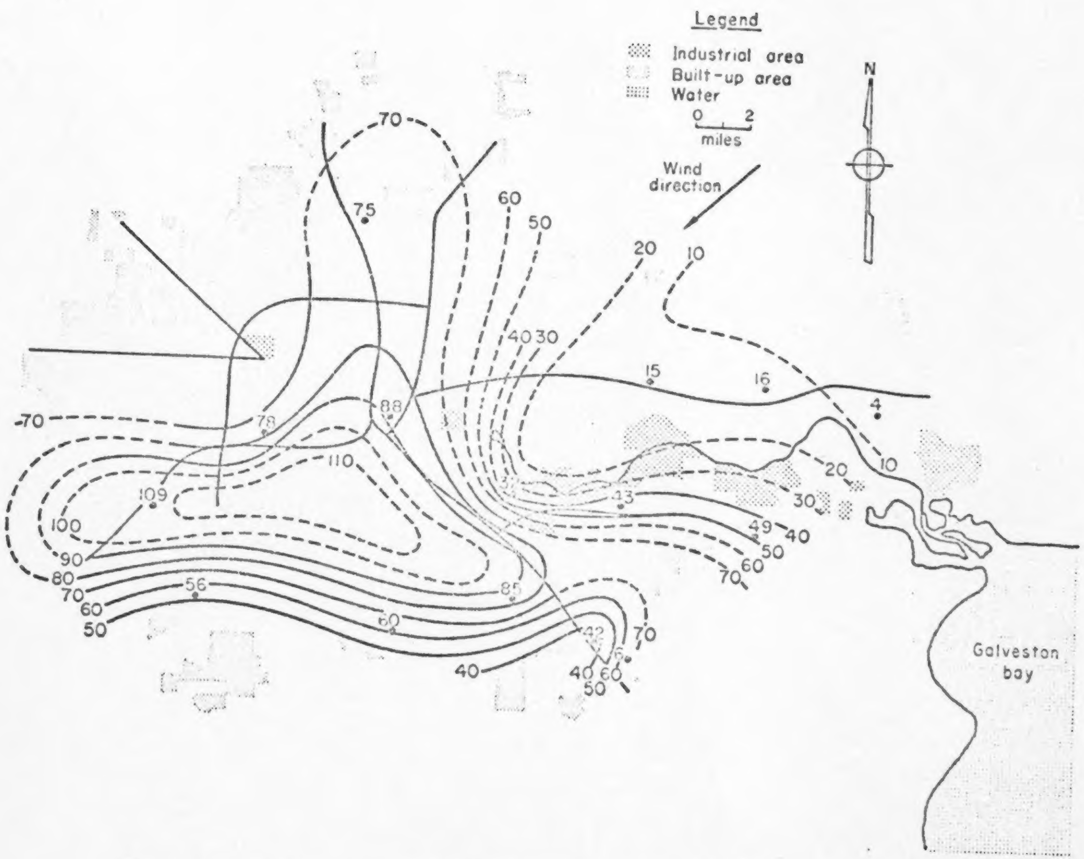
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FIG. 5. Normalized concentrations of Br × 10^{-2} μg m^{-3} during a 24 hr period on 28–29 December 1967. Dashed contours indicate regions of uncertainty in the analysis. Freeway locations are indicated by the solid interconnecting lines.

TABLE 2. ARITHMETIC MEAN VALUES OF THE CONCENTRATION OF Mn PARTICULATES FROM SELECTED URBAN LOCATIONS FOR 1964, IN $\mu g\, m^{-3}$

City	Concentration
Boston	0·03
Chicago	0·07
Pittsburgh	0·21

observed for Mn was 4.7 $\mu g\, m^{-3}$ in a 24 hr period. The geometric mean of the concentration was 0.063 $\mu g\, m^{-3}$. These figures are based on NASN data covering the period 1957–1964. In an early publication, TABOR and WARREN (1958) noted that in 20 cities the range of measurable Mn particulates was 0.01 to 3.0 $\mu g\, m^{-3}$. Obviously, most of the data for Houston are well above the minimum values measured, and, in particular, they are larger than the geometric mean from the NASN data for the 1957–1964 period. However, the data presented in FIG. 4 are only for one, 24 hr period so that no sound conclusions can be drawn regarding the amount of Mn normally in the atmosphere over Houston. The significant points are that noteworthy amounts of Mn compounds were detected in the city and that neutron activation provides an expedient and efficient means for identifying the areal distribution of the Mn. A similar conclusion was reached recently by KEANE and FISHER (1968) in an activation analysis experiment they conducted in England.

FIGURE 5 illustrates the measured distribution of the concentrations of Br in the city. Notice that the range of the concentrations is from 0.04 to 1.09 $\mu g\, m^{-3}$. A comparison of FIGS. 4 and 5 reveals that the orientation of the concentration fields is very similar, however, at many of the sampling sites more compounds of Br were sampled than those of Mn. Of particular importance is the fact that the largest Br densities occurred west of the ship channel and that the maximum measured value was in the extreme western portion of the city. This part of Houston consists primarily of residential tracts.

There are no known significant sources of Br compounds in the city; consequently, an explanation for the relatively large concentrations is difficult to propose. One possible source would be exhaust gases from motor vehicles. Bromine is present in gasoline as the anti-knock additive ethylene dibromide. According to HIRSCHLER (1964), the element Br can be exhausted as a particulate in the form $PbCl \cdot Br$ as well as $NH_4Cl \cdot 2PbCl \cdot Br$ or $2NH_4Cl \cdot PbCl \cdot Br$.

Some 24 hr traffic count data were available from the Texas Highway Department and from the City of Houston. In general, these data were collected during the period 1965 to early 1967. These data are tabulated in TABLE 3 to illustrate the estimated vehicular movement only along freeways. In this table notice that the smallest traffic count occurs at the station with the largest observed concentration of Br. Reference to FIGS. 1, 2, and 5 reveals that the mean wind direction was nearly parallel to the freeway near Station 1. Consequently, this air flow condition would have transported the exhaust effluvia southwestward along the freeway, causing exhaust pollution to accumulate rapidly in the air. In 1966, 60,000 vehicles were counted on this freeway at an intersection approximately 3 miles NE of Station 1. For this reason, it is proposed that the concentration at Station 1 probably is correct and is due to exhaust gases which accumulated in the air passing this station.

Table 3. Selected traffic counts near sampling stations and along freeways in Houston during the period 1965–1967

Station No.	Year	Traffic count	Br(μg m^{-3})
1	1967	16,700	1.09
3	1965	75,600	0.78
4	1965	43,800	0.75
5	1965	61,000	0.88
7	1965	65,000	0.85

Figure 1 shows that stations 1, 3, 4, 5, 7, 9, 10, 11, 12, and 14 are located within 1 mile of freeways carrying high-volume traffic. During the morning and evening rush hours, only stations 5 and 7 were situated on the leeward side of the freeways. Consequently, these two stations probably would have sampled more particulate matter from automobile exhausts than the other stations. Notice, in Fig. 5 and in Table 3, that two of the largest concentrations did occur at these two stations.

Measurements of the natural background content of Br in the atmosphere were made through neutron activation by Winchester and Duce (1968) near Fairbanks, Alaska. Data from 10 samples taken at a site 7 km west of downtown Fairbanks revealed that the possible background Br content of the air ranged from 0.021 to 0.065 μg m^{-3} with a mean of 0.035 μg m^{-3}. In a separate experiment, 20 measurements were taken in downtown Fairbanks. The range of the downtown concentrations was from 0.14 to 1.24 μg m^{-3} with a mean of 0.50 μg m^{-3}, revealing that the concentrations in the polluted city air were at least an order of magnitude greater than those values obtained outside the city. Preliminary results from a study in downtown Cambridge showed that for this maritime environment the range of the concentration of Br was from 0.02 to 0.8 μg m^{-3} with a mean value of 0.2 μg m^{-3}. These statistics were compiled from only 10 samples. Notice that the measurements from downtown Cambridge and Fairbanks are compatible with those taken in Houston.

In another study, Duce *et al.* (1965) conducted sampling experiments on the island of Hawaii. Nearly 200 samples of rainwater, aerosol, and gas were collected west of Hilo and over the ocean east of Hilo during the summer of 1963. The results of activation analysis of these measurements disclosed that the concentrations of Br ranged from 0.007 to 0.023 μg m^{-3} with a mean value of 0.017 μg m^{-2}. These data were considered to be representative of a maritime background count for Br. Notice, in Fig. 5, that all the Br concentrations for Houston are larger than this mean value and that most of them are an order of magnitude larger than the maximum value measured on Hawaii.

Of the total mass of the particulates measured per unit volume, the Br accounted for 1 per cent of the total mass and the Mn only 0.1 per cent. Most of the particulate matter was probably dust or other dispersoids which were not detected because of very short half-lives or because their peaks could not be detected until after the ^{56}Mn and ^{82}Br had decayed significantly.

5. SUMMARY

It has been demonstrated that neutron-activation is an expedient means for identifying the composition of particulate matter deposited on filter paper in high-volume samplers. The identification is by element only and high resolution is provided with good accuracy into the pg range. It is recommended that further use be made of this technique for identifying atmospheric constituents, especially in cities containing many high-volume samplers. The principal restriction on this technique is that the costs may be quite high; especially, if one wishes to detect numerous elements in many different samples. The average cost per sample is estimated to be between $50 and $100, depending on the elements to be detected.

Another noteworthy result is that concentration maps could be deduced from the available data and that the distributions of two particulate pollutants; namely, Mr and Br, were determined for the same time period. The primary source of Mn compounds probably would be process losses from cement companies, chemical companies, and a steel mill located upwind from the sampling stations. The range of the concentrations of Mn was from 0.02 to 0.05 $\mu g\ m^{-3}$ which is compatible with concentrations measured in other cities. It is proposed that the Br compounds may have originated from ethyl fuel combustion. The range of the Br concentrations was from 0.04 to 1.09 $\mu g\ m^{-3}$. The concentrations of the element Br were generally larger than those of Mn and are compatible with measurements taken in several other cities.

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(6)(a) A COMPARISON OF THE SPECTRAL DISTRIBUTION OF SOLAR RADIATION IN A POLLUTED AND A CLEAR AIR MASS

Sampling the spectral distribution of the energy intensity of solar radiation passing through a horizontal plane was conducted during the period 12:00-12:45 C.S.T. (18.00-18.45 G.M.T.), 12 November 1968 in Houston, Texas (lat. 29°46'N). This day was selected because the sky was free of clouds and because the synoptic weather regime was conducive to the local accumulation of atmospheric pollutants.

An ISCO (Instrumentation Specialities Co.) Model SR spectroradiometer was utilized to scan the visible portion of the spectrum from 0.38 to 0.7μ. This instrument was equipped with a wedge interference filter system which eliminated filter changing and permitted continuous scanning of the solar spectrum from 0.38 to 0.7μ. The bandwidth of the scanning unit is 0.025μ. The half-bandwidth is approximately 0.015μ so that details of the wavelength of light sources with narrower bandwidths, such as spectral lines, could not be resolved. The spectroradiometer was calibrated with a standard lamp, 24 hr and 3 hr before, and 24 hr after the observations were taken. These calibrations revealed that the instrumental error was very small (<5%).

On 12 November 1968, southeastern Texas was under the influence of a continental polar air mass. Atmospheric soundings for Victoria, Texas, and Lake Charles, Louisiana, indicated a deep stable layer of air extending from the surface layer to near the 10,000-ft level. Only the sounding for Victoria is presented in Figure 1 because it represents the thermal structure of the atmosphere over Houston on the morning of 12 November. In Figure 1, notice that the moisture content of the air was small, with surface dew point temperatures near -1°C. Figure 1 also shows that the average mixing ratio from the surface to 10,000 ft was about 1.7%.

Analyses of winds aloft data and surface synoptic reports during the period 1200 GMT, 12 November, to 0000 GMT, 13 November 1968, indicated that between the surface and the 2000-ft level, in the vicinity of Houston, the airflow was from the NE through E. Between the 2000- and 30,000-ft levels, the airflow was from the NW. Consequently, in the boundary layer there was no advection of moisture over Houston from the Gulf of Mexico and the upper air trajectories had long tracks over the continent, minimizing moisture advection in the upper levels.

Given the 1800 GMT surface temperature at Houston, and assuming that diurnal heating created a dry-adiabatic lapse rate through the surface layer, the 1200 GMT sounding for Victoria would have permitted vertical mixing to extend to near the 2000-ft level over Houston. Since an industrial complex is located about 8 mi east of downtown Houston, the existing wind regime would have transported the industrial effluvia westward as the temperature inversion acted as a lid, trapping the pollution below the 2000-ft level. This proposed movement of pollution was verified by the fact that, at 1800 GMT in the extreme western portion of the city, horizontal visibility at the ground was limited to 3-5 mi in an orange-tinted haze. The color probably was caused by scattering of the sunlight rather than by the chemical composition of the atmospheric pollutants. Spectroradiometer measurements were taken west of downtown Houston, underneath this cloud of pollution, and at another site located approximately 15 mi NW in the apparently pollution-free air.

Results

The results of the two spectroradiometer measurements are presented in Figure 2 and in Table 1. In the figure, the solid line indicates the observed spectral intensity of light in the clear air, the dashed line the spectral intensity observed under the polluted air mass, and the dotted line the absolute global radiation calculated by Deirmendjian and Sekera (1954) for perfect scattering in a Rayleigh atmosphere. Only the spectral intensities in the 0.45-0.7μ band are presented because of equipment malfunctions in the frequency band from 0.38 to 0.425μ. No explanation is given for the fluctuations in the spectra; only the difference in the intensities is of general interest in this paper. Near 0.62μ the two spectra appear to indicate a small band of minimum energy loss; however, this effect was the result of a slight slippage of the drive-head mechanism in the instrument. The net loss of energy for 0.025μ bandwidths is presented in Table 1.

In Figure 2 the difference between the light intensity in the clear air and in the polluted air is quite apparent. In particular notice that the shape of both curves is very similar. This resemblance implies that the same type particulate matter might be present in the clear air as in the polluted air, but in greater quantities in the latter. Deirmendjian and Sekera (1954) noted a similar effect due to the increased opitcal thickness of the atmosphere in the years immediately following the Katmai eruption. They assumed that if the sky radiation were unaffected, then the suspended volcanic dust should act as a neutral filter in the high atmosphere, absorbing radiation uniformly at all wavelengths. A similar type analogy could be proposed tentatively to account for the loss in energy between the two observed spectra.

A comparison of the two observed spectra with the theoretical spectrum of Deirmendjian and Sekera reveals an interesting similarity in shape. According to these two authors, the irregularities appearing in their spectrum in the region of wavelengths shorter than 0.6μ correspond to the Fraunhofer absorption regions. No conclusive explanation is offered for the sharp increase in energy near 0.61μ, except that it might be the result of increased reflection by some constituent in the atmosphere.

To determine the net decrease in spectral intensity for intervals of 0.025μ, both of the observed spectra were integrated by utilizing the mean-value theorem for integrals. The results of these calculations are tabulated in Table I. In the table, notice that the largest net decrease in spectral intensity occurred in the 0.45-0.47μ band while the smallest change was in the 0.675-0.7μ band. Approximately 31% of the light intensity per 0.025μ band is consistent with scattering theory.

The total amount of energy available in the clear air was 0.35 cal cm^{-2} min^{-1} in the 0.45-0.7μ band while the total energy available under the polluted air mass was only 0.27 cal cm^{-2} min^{-1}. Consequently, there was about a 23% loss in the total evergy that was apparently available in the 0.45-0.7μ band. This calculated loss in energy should be reliable because the two observation sites were only about 15 mi apart and because the time interval between the observations was only 30-40 min. Of particular interest is the fact that the 23% loss in energy is consistent with the estimate made by Sheppard.

Summary

According to Brooks, (1959) the 0.61-0.7μ band is the region of strong photosynthetic activity in plants as well as the band of strongest photoperiodic activity in many plants. Table 1 indicates that, in the 0.61 - 0.7μ band, about 18.5% of the available energy of light was lost through attenuation by airborne particulates in the polluted air mass. Consequently, this polluted atmospheric region was filtering out a portion of the light spectrum which is important to plant life. Brooks also noted that the 0.4-0.51μ band is important to plant development. Table 1 illustrates, in this band, probably at least 31% of the light intensity was depleted by pollution. Calculations of the energy loss in the 0.425-0.45μ band indicated about a 32%

depletion; however, instrumental errors did exist in this band.

The most noteworthy result achieved in this experiment was that some evidence was obtained to illustrate the role played by atmospheric pollutants in depleting the visible portion of the solar spectrum. The calculations reveal that approximately 23% of the available light energy was lost through diminution by pollution in the 0.45-0.7μ band. As expected, this loss was wavelength dependent, the short wave-lenghts being scattered more than the long wavelengths. Absorption by O_3 probably was occurring in the Chappuisbands, between 0.45 and 0.65μ; however, O_3 absorption in these bands is weak.

Since approximately 30% of the nation's oil refining capacity is located in the Houston-Galveston industrial complex, large quantities of hydrocarbons along with the exhaust effluvia from heavy, rush-hour traffic combine to create a polluted environment with the potential for forming O_3 as the sunlight becomes intense enough for photochemical reactions to occur rapidly. Consequently, it is possible that some of the loss in radiant evergy was due to absorption through photochemical reactions in the polluted air mass. A more quantative analysis is not possible because of the complex chemical composition of the polluted air.

If the 32% loss in energy in the 0.425-0.45μ band is correct, then the total depletion of the evergy available in the 0.425-0.7μ band would be about 24%. The data from the shorter wavelengths indicated that even more evergy probably was lost in the band from 0.38 to

0.425μ; however, these data were not reliable. The orange color of the sky indicated that scattering was occurring so that a significant portion of the short-wave radiation was depleted by the polluted air mass. Consequently, it seems reasonable to assume that the calculated 23-24% loss in energy is a minimum value and that the total loss in the visible portion of the spectrum must be even greater. If this depletion in light persists for 2 or 3 days, as it might in a severe pollution episode, a physiological response, as observed by Heck and Dunning (1967), probably occurs in plants and animals; however, presently, the effects of this response are not defined clearly.

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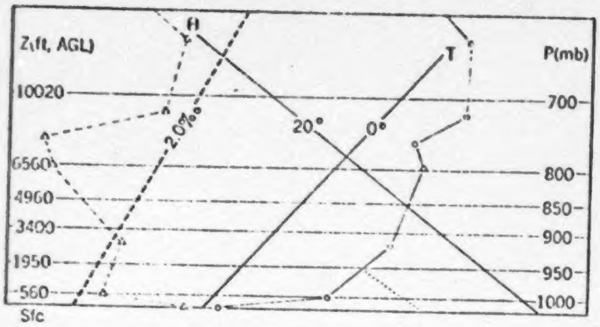

Figure 1. A Skew-T, Log-P sounding for Victoria, Texas, taken on 12 Nov., 1968, at 1200 GMT. The solid line with the circles represents the temperature sounding while the dashed line connecting the triangles represents the dew point temperature sounding. The dotted line extending from near the base of the temperature sounding represents the estimated, noon, temperature lapse rate over Houston, Texas.

Table 1. Intensity of light in the 0.45–0.7μ band for 0.025μ bandwidths.

Wave-length λμ	Clear air, Φ_c(μW cm^{-2})	Polluted air, Φ_p(μW cm^{-2})	Net loss, %
0.45-0.475	2,282.5	1,575.0	31
0.475-0.50	2,485.0	1,775.0	29
0.50-0.525	2,445.0	1,800.0	26
0.525-0.55	2,385.0	1,787.5	25
0.55-0.575	2,537.5	1,937.5	23
0.575-0.60	2,570.0	2,006.3	22
0.60-0.625	2,562.5	2,025.0	21
0.625-0.65	2,287.5	1,837.5	20
0.65-0.675	2,350.0	1,937.5	18
0.675-0.70	2,155.0	1,832.5	15
	24,060.0	18,513.8	

Calculations:

Φ_c = 24060.0 μw cm^{-2} = 0.35 cal cm^{-2} min^{-1}

Φ_p = 18513.8 μw cm^{-2} = 0.27 cal cm^{-2} min^{-1}

$\Phi_c - \Phi_p$ = 5546.2 μw cm^{-2} = 0.08 cal cm^{-2} min^{-1}

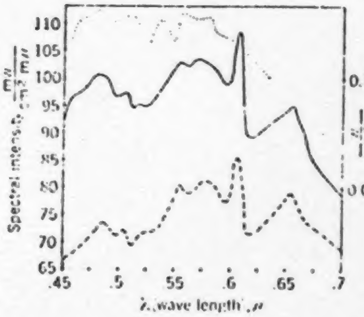

Figure 2. Spectroradiometer measurements taken at about noon local time in Houston, Texas, on 12 Nov. 1968 in clear air (——) and polluted air (- - - -). The spectral line (....) represents perfect scattering in a Rayleigh atmosphere, after Deirmendjian and Sekera.[8]

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(6)(b) SOME ASPECTS OF THE FORM OF HOUSTON'S HEAT ISLAND

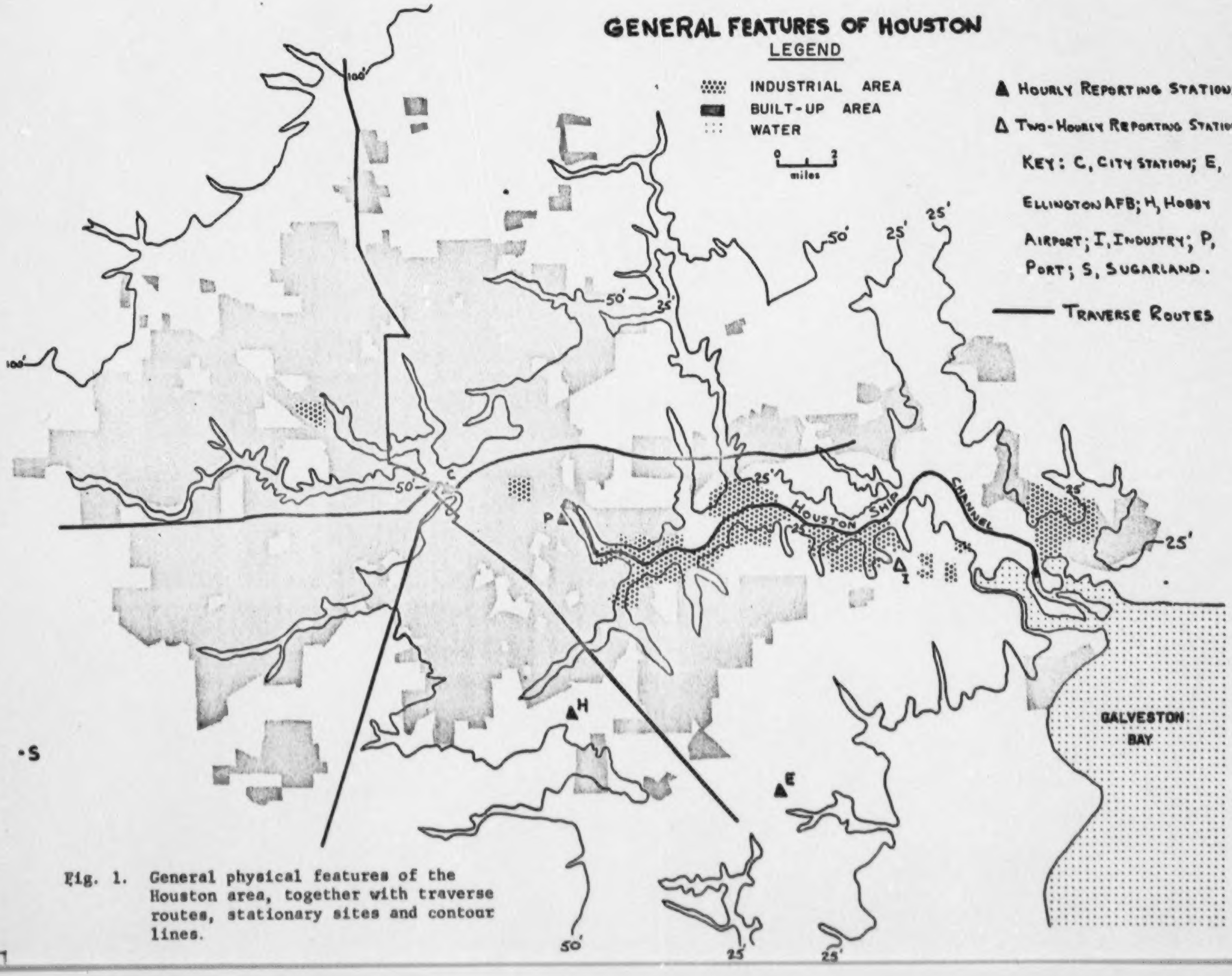
Introduction

The dispersal of pollutants over an urban area by atmospheric diffusion depends on the vertical variation of temperature and the mean velocity and turbulent characteristics of the wind. The depth of atmosphere into which the pollutants will be dilluted is determined by the variation of air temperatures in the vertical and by the vertical component of the atmospheric turbulence while the mean wind speed and lateral turbulence essentially determine the horizontal spreading of pollutants.

The urban landscape, consisting of a complexity of streets, factories, shops, houses, offices and open spaces, effects both the turbulence conditions and the heat balance of that portion of the atmosphere in contact with the urban surface (Landsberg, 1970). The increase in the surface roughness (as compared with the surrounding non-urban areas) tends to reduce the wind speeds near the surface. The discrete nature of the surface elements (buildings, etc.) tends to increase the number of small-scale turbulent eddies. The heat balance of the urban atmosphere is changed when surfaces of low heat conductivity (indicative of the rural area) are converted to surfaces with large capacity for absorbing and storing heat. The relatively larger amounts of heat that are stored in the materials making up the urban surface are released throughout the night, tending to offset the effects of radiational cooling. In addition the heat energy produced during the burning of fossil fuels and the reduced diffusive transport capacity of the wind near the surface tend to further offset the cooling effects of outgoing radiation.

In an effort to evaluate the thermal modification of the regional climate by the Houston urbanized area, a measurement program was initiated to ascertain the extent of the urban "heat island." This feature of most cities is, in essence, a mass of warm air that rests above and within the built-up area of a large community. The spatial delineation of this thermal pattern is important if a realistic characterization of the vertical variation of temperature is to be incorporated in a model of pollutant diffusion.

Area of study. Figure 1 shows some general features of the Houston region. The area within which temperature measurements were made corresponds to the major portion of the built-up area. The topography of this area is extremely simple. Thus, temperature variations due to changing elevations are essentially negligible. The range of elevation of the study area is from approximately 25 ft. mean sea level (msl) to 100 ft. msl and the slopes are quite gentle. The portions of the area in which large amounts of heat energy are produced by industrial activities are shown with large stipling. The built-up area consists of residences, commercial establishments, offices and streets. Large open-spaces are shown within the built-up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HOUSTON SHIP CHANNEL
GALVESTON BAY

Fig. 1. General physical features of the Houston area, together with traverse routes, stationary sites and contour lines.

area.

Form of Houston's Heat Island

Average intensity. A heat island exhibits an intensity as well as a shape. A measure of the average intensity of Houston's heat island is the variation in the daily minimum temperatures near the center of the city and at some nearby rural site. Figure 2 shows the average values of the minimum temperatures for each month during the years 1931-60. Averages for the city office of the National Weather Service and the station of a cooperative observer at Sugarland, Texas (see Figure 1) are used. The magnitude of the heat island is approximately 3.0°F which is typical of the value based on daily mean temperatures in other major cities (Landsberg, op. cit.). The intensity of Houston's heat island based on daily mean temperatures is only 0.1°F, when the above-mentioned stations are used.

Observational study. The measurement program was designed to study the form and intensity of Houston's heat island during the nighttime hours in early winter. The city is susceptible to heavy concentrations of air pollutants in early and late winter when it is under the influence of cool anticyclones. During the early winter and late fall months, the leading edge of the cool air associated with the anticyclone will move over the Gulf of Mexico until the opposing force of the sub-tropical anticyclone retards further movement. Approximately two to four days after the passage of the leading edge of cool air through the Houston area, the winds associated with the anticyclone are very light and are from the north-to-east quadrant. The cool

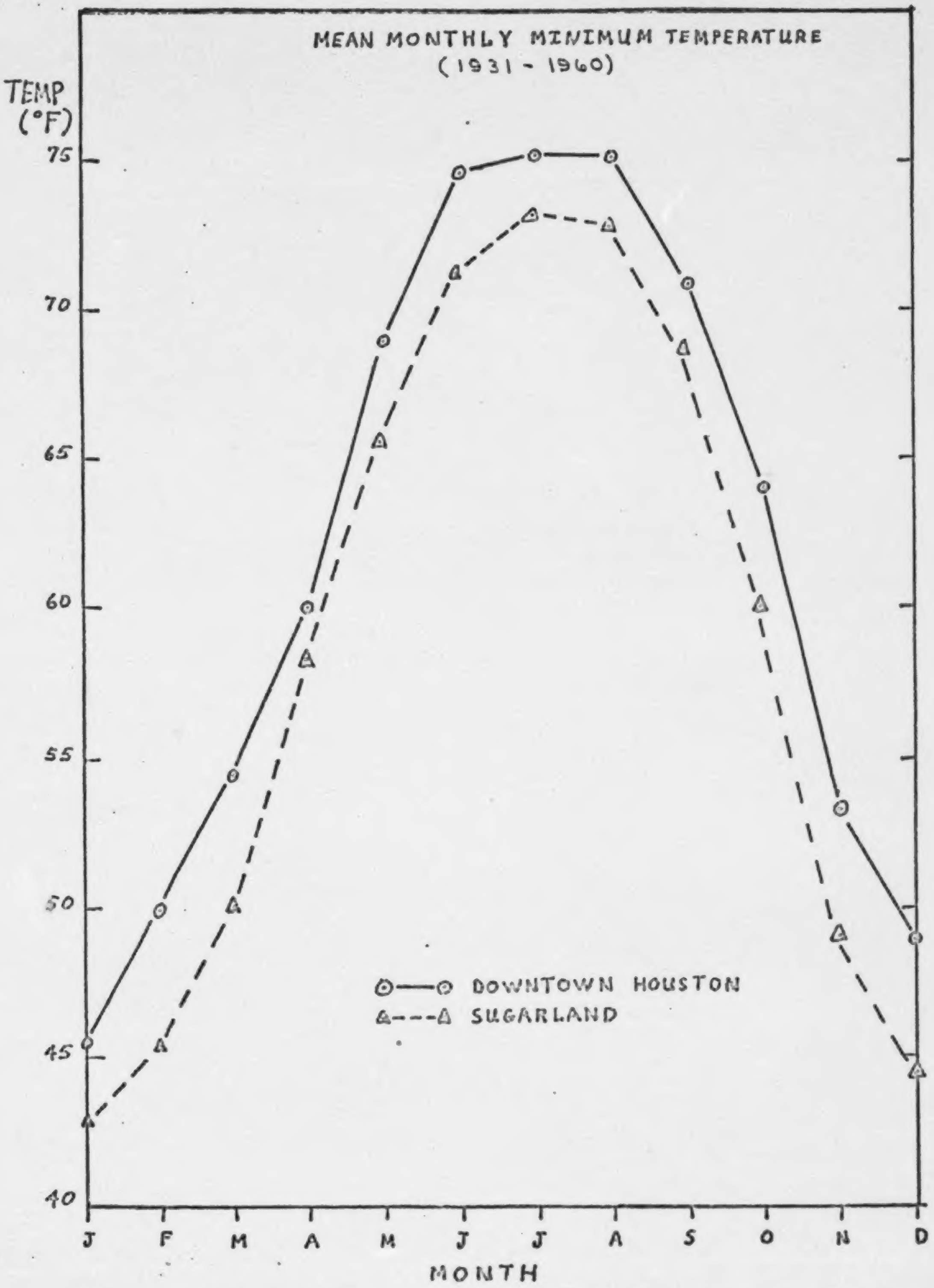


Fig. 2. Mean monthly temperatures for the period 1931-1960 for Houston and surburban site at Sugarland.

air associated with the anticyclone is several thousands of feet thick and during daylight hours its lower portions are heated from contact with the warm surface. Figure 3 shows the vertical temperature variations over the built-up portion of Houston at 1645 Central Standard Time (CST) two days prior to the period in which horizontal measurements of temperatures were made. The synoptic pattern changed very slightly between these two times and the pattern shown in Figure 4 is representative of meteorological conditions at the surface over southeast Texas during the times that temperature data were collected.

Method of measurement. The horizontal pattern of temperatures was determined from data collected during automobile traverses. These measurements were supplemented by data from four hourly-reporting stations and one industrial plant which measured air temperatures at two-hour intervals. The traverse routes together with the locations of the fixed stations are shown in Figure 1.

During an 18-hour period beginning at 1900 CST on 28 December 1967 five two-way traverses were made along each of the routes. The time of the traverses varied with traffic conditions, but an approximate duration was two and one-half hours for the out-and-back trip. Out-and-back traverses along the northern and southeastern routes were made between 1400 and 1600 CST on 29 December. Outward traverses on the eastern, southwestern and western routes were commenced also at 1400 CST.

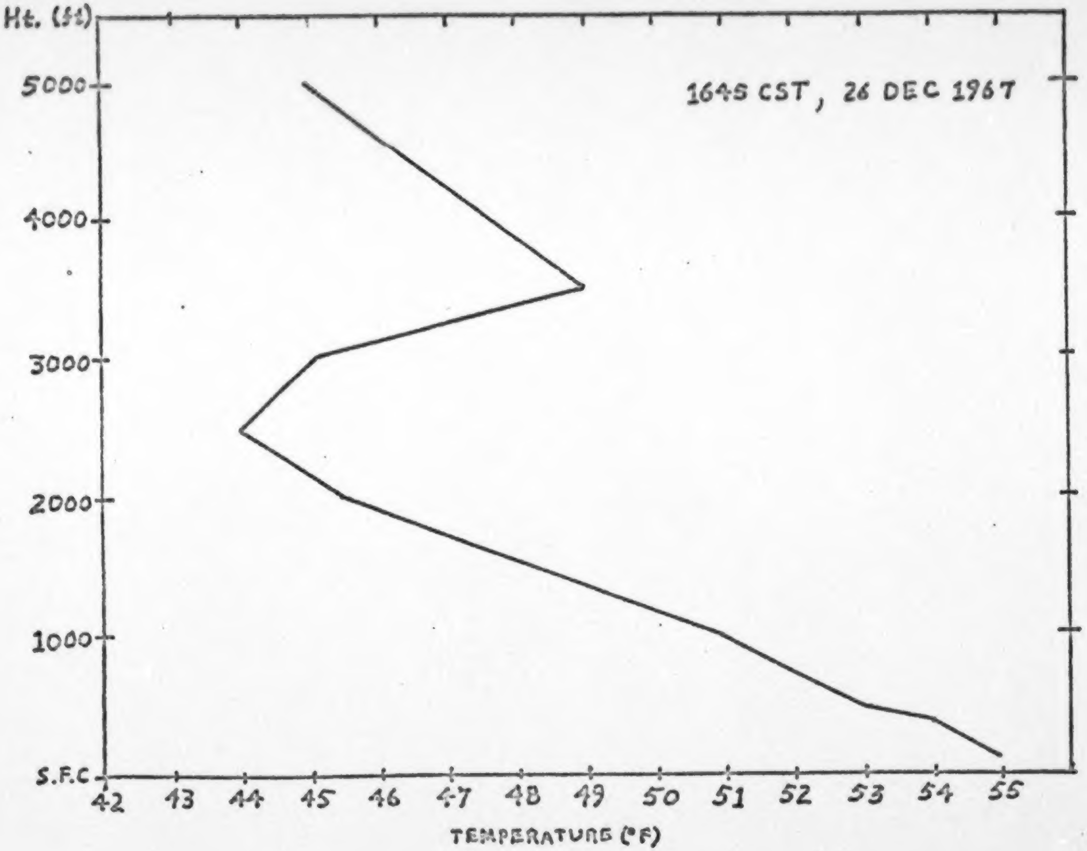
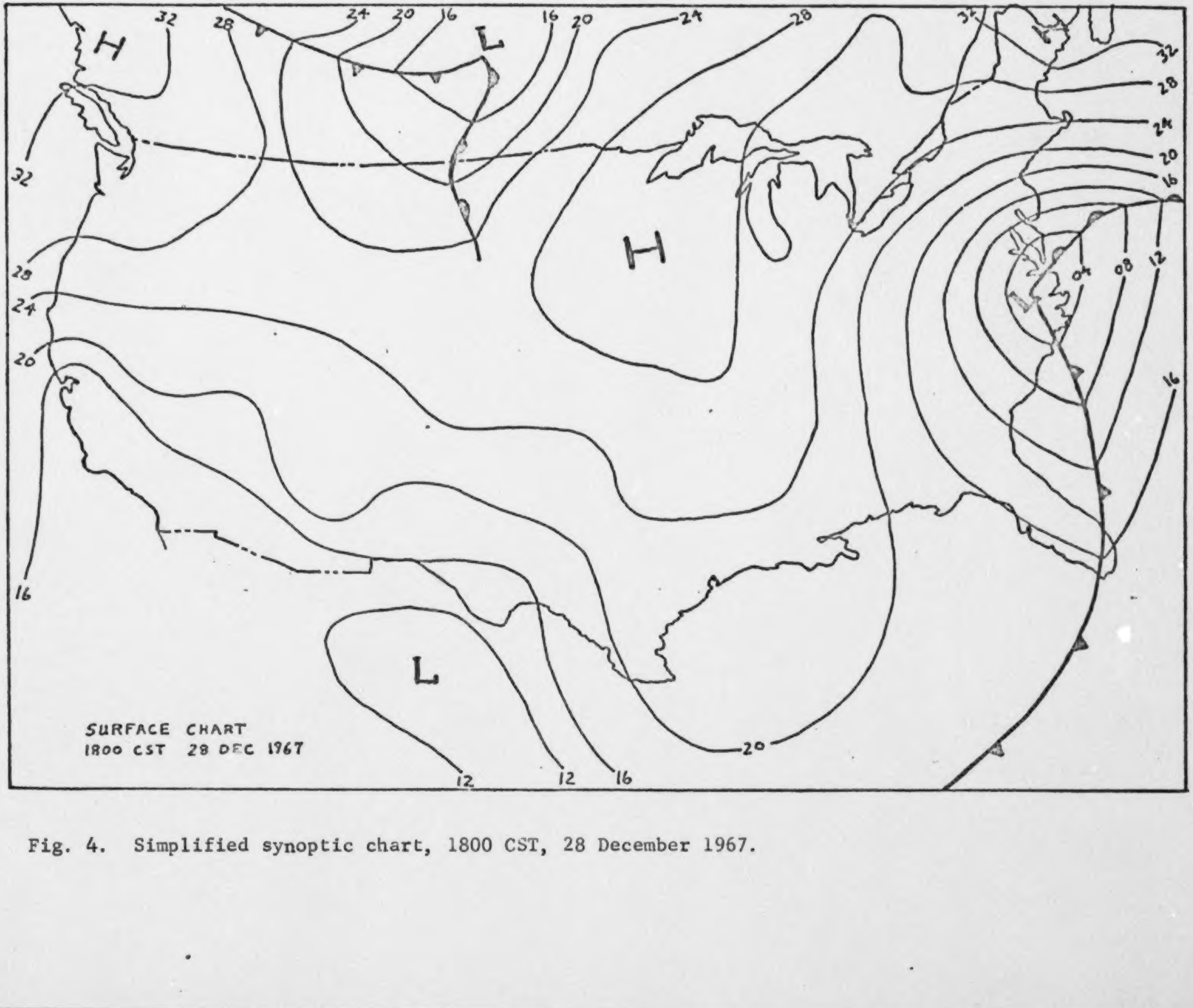


Fig. 3. Vertical variation of temperature over the built-up area of Houston, 1645 CST, 26 December 1967.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04
08
12
16
20
16
12
12
32
28
24
20
16

Fig. 4. Simplified synoptic chart, 1800 CST, 28 December 1967.

Table 1 summarizes the time intervals during each traverse.

Table 1 Duration times of each traverse.

Traverse	Approximate times (CST)	Day
1	1915-2145	28 Dec. 1967
2	2300-0130	28-29 Dec. 1967
3	0300-0500	29 Dec. 1967
4	0700-0945	29 Dec. 1967
5	1030-1245	29 Dec. 1967
6	1400-1600	29 Dec. 1967

Stops were made at intervals of approximately two miles along each route. At distances removed from the proximity of the heated automobiles, dry-and wet-bulb temperature measurements were made. The number of stops averaged nine per route (a total of 45) with a range of eight to ten stops per route. Measurements were made at these stops on both the outward and inward portions of each traverse.

Temperature variations in the vertical direction were measured by Dr. Darryl Randerson in a helicopter using a psychrometer. These measurements were made between 1612 and 1707 CST on 26 December 1967. Since the synoptic pattern changed little during the time from the afternoon of the 26th to the commencement of the horizontal measurements on the 28th, we felt that the vertical pattern shown in Figure 3 was indicative of conditions in the lower atmosphere during the early evening hours on the 26th.

Analysis of Data. The dry-bulb temperature measurements obtained at each stop together with the measurements from the fixed stations were plotted as functions of time. Thus a total of 49 temperature vs. time graphs were produced. The uniform data from the fixed stations permitted estimations of the temperature variability for those time intervals between stops along the traverse routes.

Figures 5,6,7 and 8 show analyses of the horizontal temperature patterns at 2100 CST on 28 December and 0000, 0300 and 0600 CST on 29 December, respectively. Although data were collected after sunrise on the 29th, an analysis was not performed since the exposure of the unshielded thermometer bulbs to direct solar radiation vitiated some of the measurements.

The spatial distribution of temperatures is the frequently observed one in which temperatures over built-up areas exceed those measured in open spaces (Peterson, 1969). The heat island is readily apparent at all four times. The temperature gradient is the largest during the times prior to midnight. Between 0000 and 0300 the patterned is noticeably "flattened" over the inner districts of the city.

In addition to the heat island, an area of elevated temperatures (analogous to topographical ridge) can be seen in the four analyses. This appears to be related to heat and pollution arising from industrial activity. Manufacturing in the Houston area rejected approximately 2.2 X 10^{11} calories of heat per 24 hours in 1967. A large percentage of this energy was emitted in the form of sensible heat by industries close to the Houston Ship Channel. The approximate axis of the "heat ridge" is along this body of water. After 2300 CST on 28 December, winds, although light, were steady from the northeast for several hours. The southwesterly advection of warm air into parts of the city lying southeast of the center could ac-

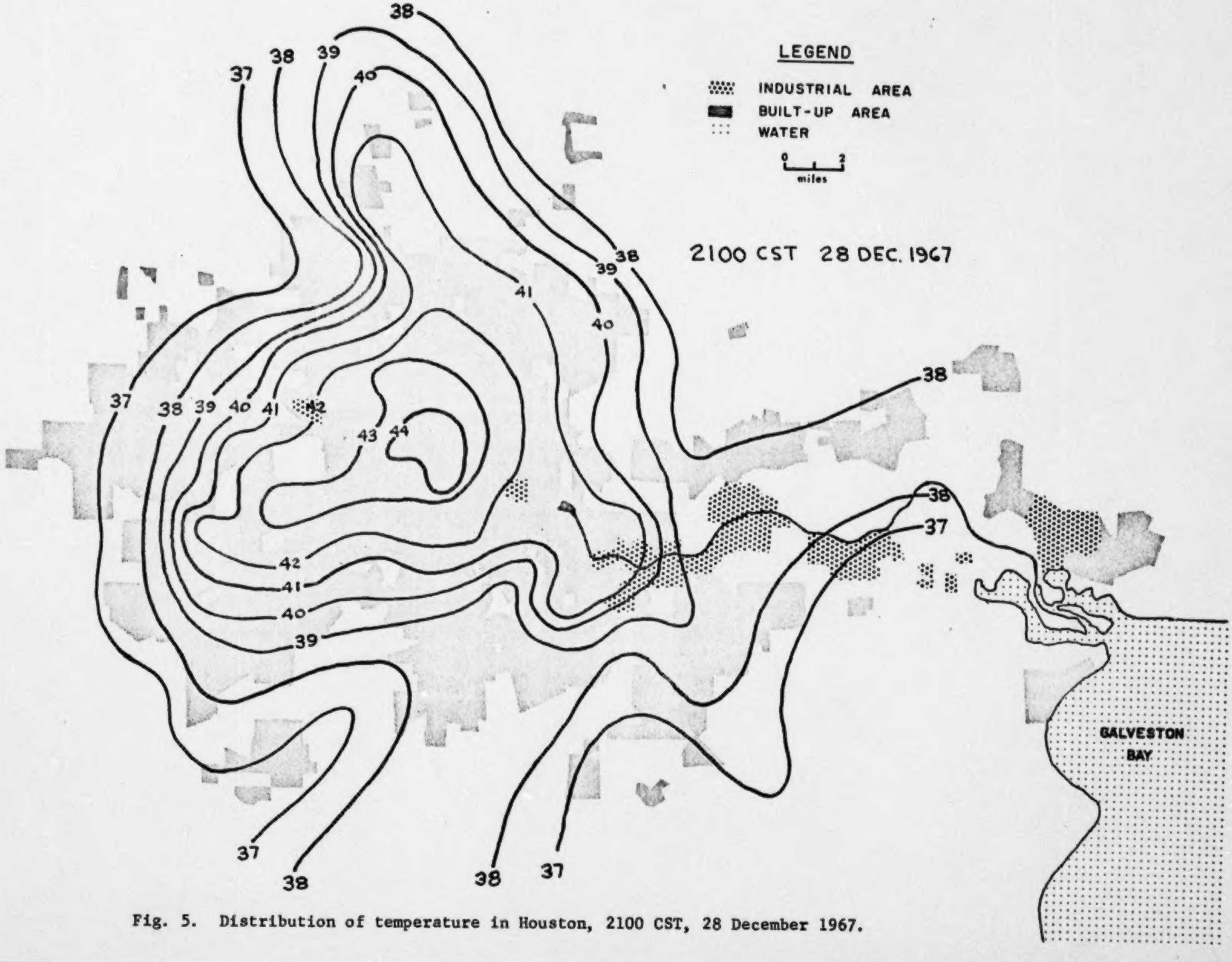
LEGEND
▨ INDUSTRIAL AREA
■ BUILT-UP AREA
∷ WATER
0 2
miles
2100 CST 28 DEC. 1967
GALVESTON BAY
37
38
39
40
41
42
43
44

Fig. 5. Distribution of temperature in Houston, 2100 CST, 28 December 1967.

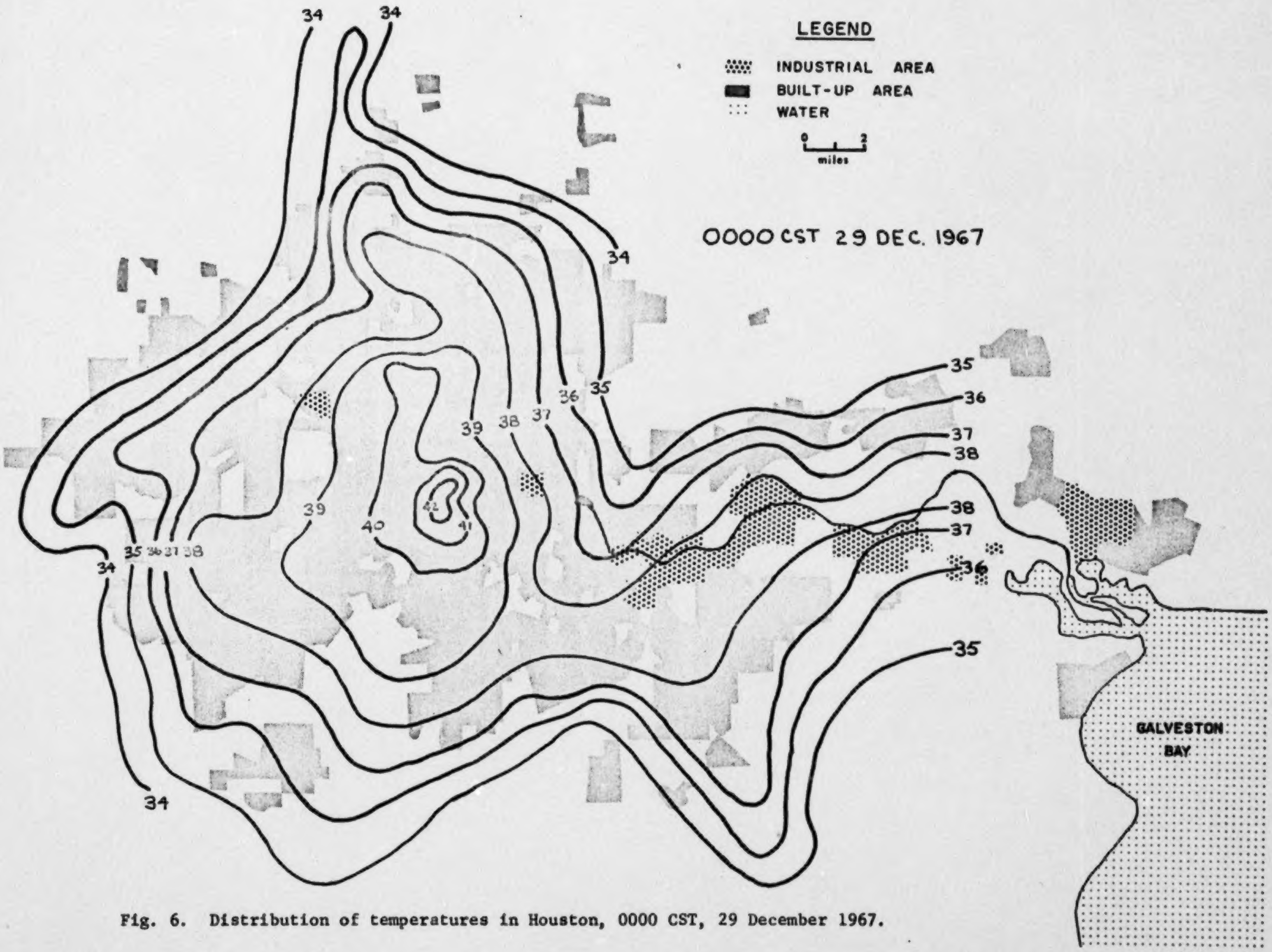
34
34
LEGEND
INDUSTRIAL AREA
BUILT-UP AREA
WATER
0
2
miles
0000 CST 29 DEC. 1967
34
35
36
37
38
38
37
36
35
35
36
37
38
39
39
40
41
41
35 36 37 38
34
34
GALVESTON BAY

Fig. 6. Distribution of temperatures in Houston, 0000 CST, 29 December 1967.

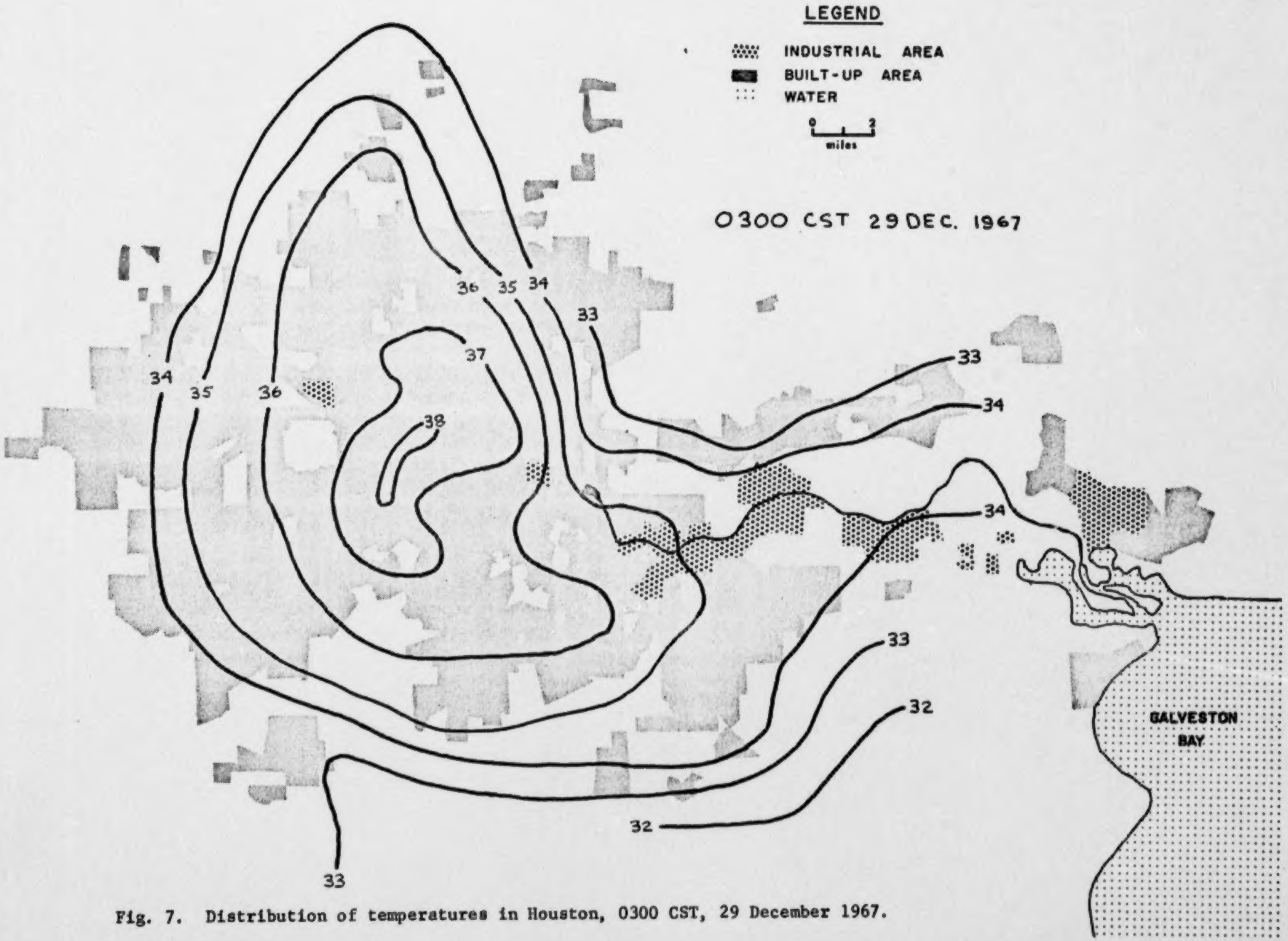
LEGEND
INDUSTRIAL AREA
BUILT-UP AREA
WATER
0
2
miles
0300 CST 29 DEC. 1967
34
35
36
37
38
33
32
GALVESTON BAY

Fig. 7. Distribution of temperatures in Houston, 0300 CST, 29 December 1967.

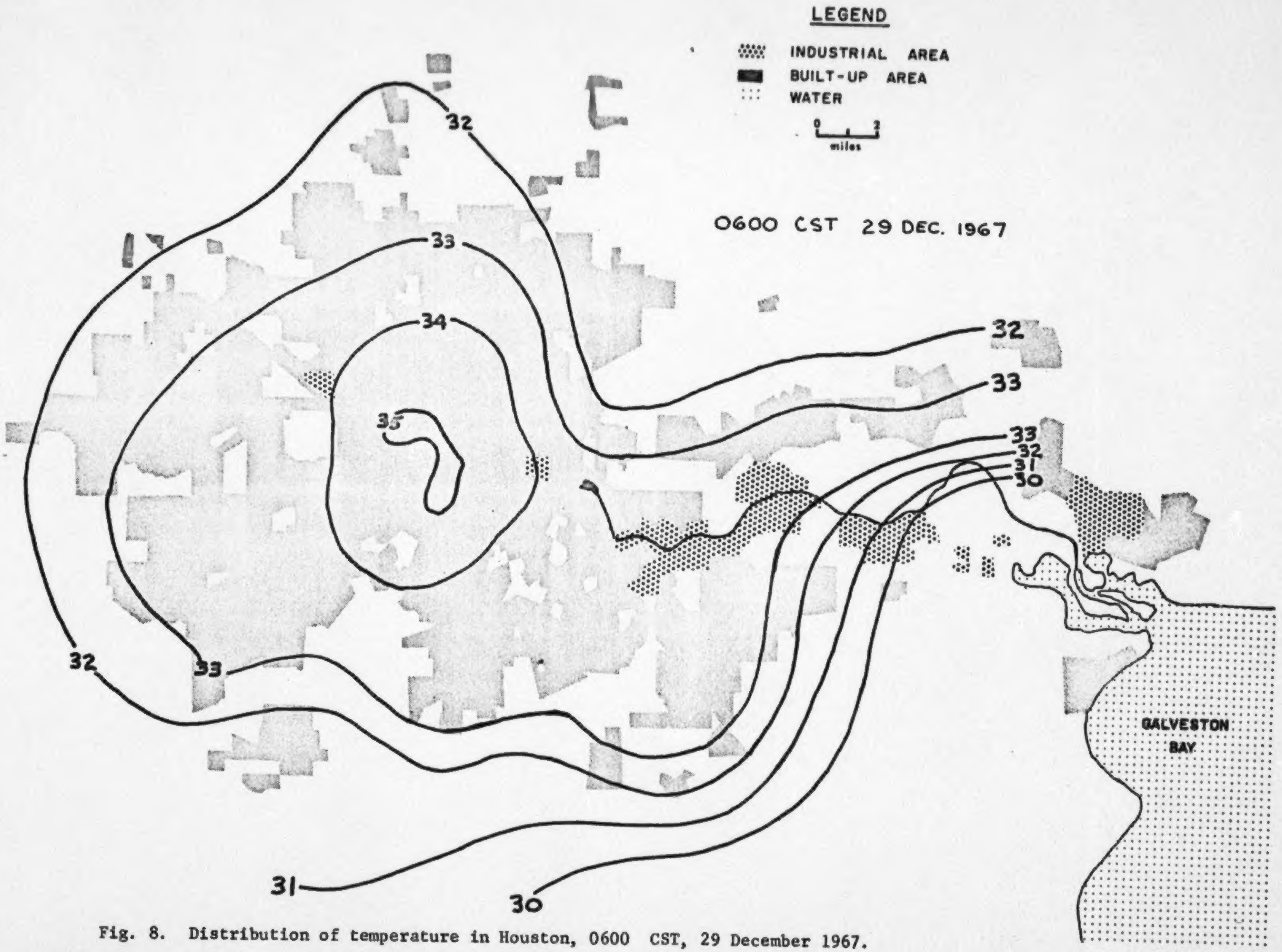
LEGEND
INDUSTRIAL AREA
BUILT-UP AREA
WATER
0 2
miles
0600 CST 29 DEC. 1967
32
33
34
35
32
33
33
32
31
30
32
33
31
30
GALVESTON BAY

Fig. 8. Distribution of temperature in Houston, 0600 CST, 29 December 1967.

count for the extension of the heat ridge into these parts of the community.

In addition to the effects of heat advection in producing this heat ridge are effects of air pollution. In the hours after sunrise on the 29th a plume of pollution was observed extending downwind (toward the southwest) from the industrial area along the channel. Kratzer (1956) and Sheppard (1958) have attributed urban heating to the absorption and re-emission downward of thermal radiation. The axis of the pollution plume passed south of the center of the heat island so the effect of pollution on the formation of this effect was probably small.

Summary

During those periods of the year when ventillation of pollutants is least, the form of Houston's heat island is not unlike those of other large cities. Temperatures over the built-up portions of the city are larger than those over nearby open spaces with the spatial variation culminating in the well-known heat island near the city center. In addition to the heat island, a heat ridge was observed on a day of high pollution potential. This ridge appeared to be the result of the retardation of outgoing solar radiation by pollution and the advection of heat energy, both attributable to industrial activity.

The relatively warmer portions of the built-up area may offset any tendency toward stability of the lower atmosphere in contact with the urban surface. Any model of atmospheric dispersions must take into account the effect on the stability of the air by these urban heat sources.

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Peterson, J.T., The Climate of Cities: A Survey of Recent Literature, Publ. AP-59, National Center for Air Pollution Control, Raleigh, N.C., 1969, 48 pp.

Sheppard, P.A., 1958: "The effect of pollution on radiation in the atmosphere", International Journal of Air Pollution, 1, 31-43.

(6)(c) REMOTE SENSING TECHNIQUES

An airborne study, by the use of a helicopter, was made over Houston, Texas, on November 18, & 19, 1970. The purpose of the study was to obtain infra-red pictures, ultra-violet measurements, infra-red data, and temperature profiles over downtown Houston and over the Houston ship channel. Use was made of color photography in addition to false-color IR photography in order to compare various areas of interest. Polarized lens filters were used to increase the visible contrast between the smoke plumes and the surrounding air. This technique allows for better visual perception of the plume extent. Upon development of the film, a photodensitometer was used to study areas where air pollution caused increased backscattering of the incident radiation. The photodensitometer measurements showed a decrease in the relative intensities in the areas surrounding the smoke plume. A constant or small increase in the relative intensities was noted while in the vicinity of the plume. No accurate measurements could be made, however, because of the film size. The 35 mm film was not large enough to be used adequately in this technique. It is believed that 70 mm film may be used with better results.

Ultra-violet measurements were taken in both upward and downward positions to determine the depletion of the UV portion of the spectrum due to the pollution. Measurements were taken every 1,000 ft from 1,000 to 10,000 ft. Values showed an increase from 4800 $\mu W/cm^2$ at 1,000 ft to 5300 $\mu W/cm^2$ at 10,000 ft with the instrument pointing upwards. In the downward position, values ranged from 250 $\mu W/cm^2$ at 1,000 ft to 400 $\mu W/cm^2$ at 10,000 ft. Ratios of up measurements to down measurements give a range from 12.5 to 17.3 with an average value of 14.7.

Temperature measurements were made by the use of a thermistor probe throughout the flight. A vertical sounding was taken during the morning from the surface to 700 mb (approximately 10,000 ft). Additional soundings were plotted from Lake Charles, Louisiana, and Victoria, Texas, for the same date and showed a close agreement. Levels were determined where pollution concentrations were expected to be high. These levels of supposed higher air pollution concentrations corresponded to variations in the UV measurements.

A Barnes infra-red sensor was used to obtain radiation values in rural areas and in the downtown region. Values in the central business district of Houston, Texas, ranged from 6°C to 15°C. The wide range of values is found because of the instrument sensitivity and the low level (1,000 ft) at which the measurements were taken. This sensor has an aperture opening of 7°, which provides a circular viewing area with a diameter of 120 ft at 1000 ft. These measurements were used to study the urban heat island and the heat generating potential of the downtown region. Flucturations in measurements were noted from building to building showing the variation in radiative transfer throughout the city.

(7) A WORLD SURVEY OF URBAN AIR POLLUTION

The number of people living in urbanareas has been increasing for many years, for as agriculture becomes more efficient and better developed greater numbers of people tend to favor a city life. The degree of urbanization varies greatly from country to country; for instance, Great Britain has 75-80% of its population living in the urban areas, while some other countries have only 2-5% of their population in urban regions. On a geographical basis, North America and Northwest and Central Europe have about 50% of their population in large cities while in Africa, south of the Sahara, this is down to 5%. Fig. 1 illustrates the growth of urbanization around the world, both as to numbers and percentages the degree of urbanization appears to be closely related to the per capita income.

The rate of increase, in percentage, of urbanization tends to be reduced after a level of about 50% is reached, and after 75% the value begins to falter or even to decline. Working with some of the latest figures it is found that there are about 40 cities in the world with a population in excess of two million and over a hundred with more than one million inhabitants.

In order to identify the specific details peculiar to urban areas a survey was conducted of certain aspects of air pollution in cities with more than one million population. Embassies were contacted and questionnaires, such as that shown below, submitted for each city. In general, many months elapsed before the completed forms were returned - if they ever were returned. In Tables I & II a summary of the available data is given for cities in the United States and foreign countries, respectively. From these it can be calculated (Table III) that 90% of the cities consider sulphur dioxide as a pollutant, half of these rank it as a serious pollutant. Particulates follow closely, 88% and 40% serious, followed closely by carbon monoxide, 82% and 24% serious, oxides of nitrogen, 75% and 13% serious, and hydrocarbons, 74% and 10% serious.

Of course, the estimates given by the authorities are only subjective and it is likely that some personal 'likes' and 'dislikes' have been included. For instance, Hamburg and Sydney report carbon monoxide pollution but do not list autmobiles as a source. Nevertheless, the role of automobiles and industry are paramount - the former is being dealt with, a combination of location, technology, law enforcement and increased costs will be necessary to combat the latter.

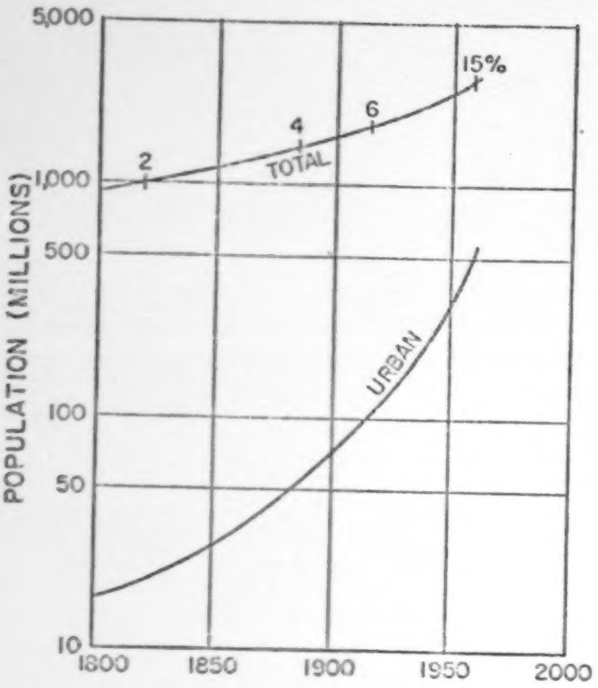

FIG. I. WORLD POPULATION AND URBANIZATION

CITY OR URBAN COMPLEX

NAME: ______________________________

POPULATION: ______________________________

AREA: ______________________________

AIR POLLUTANTS: ______________________________

____

SERIOUS AIR POLLUTANTS: ______________________________

MAJOR SOURCE OF POLLUTANTS: ______________________________

ARE POLLUTION CONTROLS IN EFFECT?: ______________

IF YES, STATE IF CITY, DISTRICT, COUNTRY LAWS:

____

NAME AND ADDRESS OF RESEARCHERS IN AIR POLLUTION STUDIES (GIVE PRIORITY TO METEOROLOGICAL STUDIES):

____

____

DATES OF SERIOUS POLLUTION INCIDENTS: ______________

____

NUMBER OF DEATHS ASSOCIATED WITH EACH OF ABOVE:

____

Fig. 2. Questionnaire

TABLE I. - SUMMARIZED DETAILS FOR U.S. CITIES

CITIES	POP. (M)	POLLUTANTS					OTHERS	MAJOR SOURCES	CONTROLS	SERIOUS INCIDENT
		SO_2	CO	NO_x	HC	PART.				
Atlanta	1.3	Y	Y	Y	Y	Y	Or, Al	A, I,	N	N
Buffalo	1.3	S	Y	Y	Y	S	SO_3	I, C	Y	N
Chicago	3.5	Y	N	Y	N	S		A, I, C	Y	N
Cleveland	1.0	Y	Y	Y	N	Y	O_3, Al, SO_3, CO_2	A, I, B,	Y	N
Dallas	1.0	N	N	N	N	Y	Ac, Metals	A	Y	N
Denver	1.1	N	Y	Y	Y	Y		A, I, B	Y	N
Detroit	1.5	Y	Y	Y	Y	S	Od	A, B, Rf,	Y	N
Houston	1.2	Y	Y	Y	Y	Y	Sm, Ac, M, Al, SO_3 O_3, Od, O, H_2S, HF	A, I, B,	Y	Y
Kansas City	1.3	Y	N	N	N	Y	O, H_2S	I, A, H	Y	N
Miami	1.2	Y	Y	Y	Y	Y	O_3, O,	A, B, I	Y	N
Milwaukee	1.1	Y	Y	Y	Y	S	Od	A, I, B	Y	N
Philadelphia	2.0	S	S	Y	N	S		A, I, P	Y	N
San Diego	1.3	N	N	S	N	S	O, Od	A, I, C	Y	N
San Francisco	4.1	Y	Y	Y	Y	S	O,	A	Y	N
Washington D.C	2.8	S	S	Y	Y	S	O,	A, P, H, I	Y	N

TABLE II - SUMMARIZED DETAILS FOR FOREIGN CITIES

CITIES	POP. (M)	POLLUTANTS SO_2	CO	NO_x	HC	PART.	OTHERS	MAJOR SOURCE	CONTROLS	SERIOUS INCIDENT
Ahmadabad (India)	1.2	Y	N	N	N	Y	H_2S			
Amsterdam (Netherlands)	1.0	Y	Y	Y	Y	Y		B, Rf, A, P	Y	N
Athens (Greece)	1.8	Y	Y	N	N	N	Sm,	A, I,	Y	N
Berlin (East Germany)	2.1	Y	Y	Y	Y	Y		A, I, H	N	N
Bogota (Colombia)	2.3	Y	N	Y	Y	Y		I, A	Y	N
Bombay (India)	4.1	S	N	Y	S	Y	H_2S	I, A, S	N	N
Brussels (Belgium)	1.1	S	Y	N	N	N	Sm	I, H	Y	N
Buenos Aires (Argentina)	6.7	Y	Y	Y	Y	S		A, B	N	N
Calcutta (India)	2.9	Y	Y	Y	S	S		A, I, C	N	N
Caracas (Venezuela)	2.0	N	Y	N	N	Y		A, B	N	N
Copenhagen (Denmark)	1.3	S	Y	Y	N	N	Sm	A, P	Y	Y
Delhi (India)	2.0	Y	N	Y	S	S		A, I,	N	N
Durban (South Africa)	1.0	S	Y	Y	Y	S	Sm, O, M, PC	A, I, C	Y	N
Hamburg (West Germany)	1.8	Y	Y	Y	Y	Y	Od, Or	I,	Y	N

Istanbul (Turkey)	1.1	S	S	N	Y	N	Sm	A,I,C,	Y	N
Johannesburg (South Africa)	1.3	S	Y	N	Y	S	Sm,	C,I,	Y	N
Kanpur (India)	1.0	Y	N	Y	N	Y		I,A	N	N
Koln (West Germany)	1.0	Y	Y	N	N	Y	F,Cl	I	Y	N
Lisbon (Portugal)	1.0	S	S	N	Y	Y	Sm	A,I,	Y	N
Manilla (Phillippines)	3.0	Y	S	S	S	S	H_2S	A,I,N	Y	N
Marsielles (France)	1.0	S	S	S	S	S			Y	N
Medellin (Colombia)	1.1	S	N	N	N	Y		I	Y	N
Melbourne (Australia)	2.0	S	S	N	S	S	HFO, SO_3	A,I,H	Y	Y
Milano (Italy)	1.6	S	S	S	Y	Y	PC	A,I,H	Y	Y
Montreal (Canada)	1.2	Y	S	Y	Y	Y	O,PC		Y	Y
Munchen (West Germany)	1.3	S	S	Y	Y	Y		I,A,H	Y	Y
Napoli (Italy)	1.2	N	Y	S	S	N	PC	A,Rf	N	N
Paris (France)	2.5	S	S	S	S	S			Y	N
Pretoria (South Africa)	1.0	S	Y	Y	Y	S	Sm,O,	A,I,C	Y	N
Rio de Janeiro (Brazil)	3.7	Y	Y	Y	Y	S		A,I, B	Y	N
Rome (Italy)	2.2	S	Y	S	S	Y		A,H	Y	N
Rotterdam (Netherlands)	1.0	S	Y	Y	Y	Y	O,F,M	Rf,P,A,I, H,	Y	Y
Stockholm (Sweden)	1.1	S	S	Y	Y	S		A,H	Y	Y
Sydney (Australia)	2.6	Y	Y	N	N	Y	Od,	Rf,P	Y	N

Taipei (Formosa)	1.5	S	Y	Y	Y	S	Sm	I, A, Rt,	Y	N
Tehran (Iran)	3.0	N	S	N	N	Y	H_2S	A,	Y	N
Torino (Italy)	1.1	S	Y	Y	S	N		A, I	Y	N
Toronto (Canada)	2.2	S	Y	Y	Y	Y	O		Y	Y
Victoria (Hong Kong)	2.1	S	Y	Y	N	N	Sm, SO_3	I, A, Rt, P	Y	Y
Vienna (Austria)	1.7	S	Y	Y	Y	S	O_3	A, I, C	N	Y

Sources

A - autos
B - incinerators
C - coal
F - fertilizer
H - household fires
I - industry
N - ships
P - power plants
Rf- refineries
Rt- restaurants
S - sewage

Others

Ac - acid
Al - aldehydes
F - fluoride
L - lead
M - mercaptons
O - oxidants
O_3 - ozone
Od - odors
Or - organic acids
Pc - petro-chemicals oil refineries
Sm - smoke

Table III

SUMMARY OF DATA FOR SELECTED POLLUTANTS

U.S. CITIES (15 TOTAL)

									SOURCE	
	SO_2	CO	NO_x	HC	PART	OXIDANTS	OZONE	SMOKE	AUTO	INDUSTRY
Y	12	11	13	9	15	6	3	1	14	12
S	3	2	1	-	8	-	-	-		

FOREIGN (40 TOTAL)

	SO_2	CO	NO_x	HC	PART	OXIDANTS	OZONE	SMOKE	AUTO	INDUSTRY
Y	37	34	28	29	33	5	1	10	29	26
S	22	11	6	10	14	-	-	-	(of 35 reporting)	